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Analysis and measurement of residual stress distribution of vanadium/ceramics joints for fusion reactor applications

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Abstract

Vanadium alloys are considered as candidate structural materials for fusion reactor system. When vanadium alloys are used in fusion reactor system, joining with ceramics for insulating is one of material issues to be solved to make component of fusion reactor. In the application of ceramics/metal jointing and coating, residual stress caused by difference of thermal expansion rate between ceramics and metals is an important factor in obtaining good bonding strength and soundness of coating. In this work, residual stress distribution in direct diffusion bonded vanadium/alumina joint (jointing temperature: 1400°C) was measured by small area X-ray diffraction method. And the comparison of Finite Element Method (FEM) analysis and actual stress distribution was carried out. Tensile stress concentration at the edge of the boundary of the joint in alumina was observed. The residual stress concentration may cause cracks in alumina, or failure of bonding. Actually, cracks in alumina caused by thermal stress after bonding at 1500°C was observed. The stress concentration of the joint must be reduced to obtain good bonded joint. Lower bonding temperature or to devise the shape of the outer surface of the joint will reduce the stress concentration.

1. Introduction

Vanadium alloys are considered as one of candidate low activation structural materials for fusion reactor system because they have low activation behavior, high temperature strength and resistance to neutron irradiation damage [1–3]. In fusion reactor systems made of vanadium alloys, Li-metal cooling system is proposed. When vanadium alloys are used in fusion reactor systems, ceramics coating such as oxide and nitride coating is available to reduce corrosion damages by Li-coolant and Magneto Hydro-Dynamic (MHD) loss.

In the application of ceramics/metals jointings or coatings, residual stress caused by difference of thermal expansion rate between ceramics and metals is an important factor in obtaining good bonding strength and soundness of joints. Stress distribution depends on material system and bonding or coating condition and geometry of joints. There are so many variations of shape of joints that estimation of each joints is difficult. Finite Element Method (FEM) analyses have been used to calculate the residual stress distribution of various shapes of joints [4].

There is much work available on ceramics/metal joints [4–7], but work on the joint pairs for fusion application are limited. Especially, there are no papers on alumina/V-alloy joint. We have studied the joints for fusion application and reported about bonding conditions and irradiation effects on bonding strength [8–11]. The purpose of this work is to study optimizing bonding conditions of vanadium/ceramics from the viewpoint of basic study, based on comparison of quantitative analysis by FEM and stress distribution using X-ray stress measurement.

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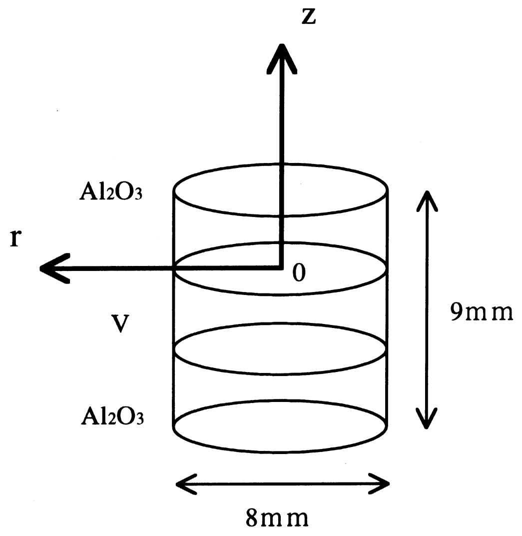

Fig. 1. The shape of the vanadium/alumina joint [8–11].

2. Experimental method

2.1. Material

In order to measure residual stress distribution, well-bonded joint pairs without crack is required. Direct diffusion bonded vanadium/alumina joints were used in this study because alumina can bond to pure vanadium without insert metals [8–11]. Fig. 1 shows the shape of the joint. The short cylinder of pure vanadium and polycrystals of alumina with 8 mm diameter and 3 mm thickness were cut from 8 mm diameter rods using a diamond-cutter. The chemical composition of the vanadium is given in Table 1. Bonding surfaces were polished with 2 μm diamond paste. These cylinders were piled up and heat-treated in a vacuum chamber (1.3×10^{-3} Pa) at various temperatures. Compressive stress (6.1 MPa) were loaded along z-axis of Fig. 1 during bonding heat-treatment. Details of the experimental procedure of bonding have been already presented [8].

Bonding was performed at temperatures between 800°C and 1400°C. There was no reaction layer observed in the boundary of the joint [12]. Previous work showed that bonding strength increased with bonding temperature up to 1400°C and cracks caused by residual stress were observed in joints bonded above 1500°C [8–11]. Therefore joints heat-treated at 1400°C might have steep shape of residual stress distribution. The joint bonded at 1400°C was used for residual stress measurement.

2.2. FEM analysis

FEM analysis was carried out by MARC code, which is an elasto-plastic FEM program. We modeled a quarter of the cross-section of the joint and used axisymmetric quadrilateral elements, which are shown in Fig. 2. At the nearest area of the boundary or the edge of the joint, there may be the steepest shape of residual stress distribution. Fine elements were used along the area to determine the detailed stress distribution. Material parameters used in this calculation are as follows: Young's modulus (E) of vanadium is 132.6 GPa and that of alumina is 359 GPa; Poisson's ratio $\nu = 0.423$ (vanadium), 0.2 (alumina). Temperature dependence of thermal expansion rate and yield stress were used as graph in the calculation. The yield strength of the vanadium at 25°C is about 140 MPa and at 1400°C is about 10 MPa in our group's results, should be published. The vanadium was treated as elastic–perfectly-plastic, and the alumina was treated as elastic. In this analysis, we assumed that the effect of work hardening of vanadium can be ignored. The calculation was made using the temperature difference. Calculation was done as the joint was bonded at 1400°C and cooled to 25°C

2.3. X-ray stress measurement

For X-ray stress measurement, the joint was cut along the center line of the joint. The cross-section was polished by diamond paste and stress distribution in the cross-section of alumina layer along boundary and outer surface of the joint was measured as is shown in Fig. 3.

Residual stress measurement was carried out using JEOL DX-MAP2 at 35 kV, 50 mA. The size of collimated X-ray beam (CuKα1) for residual stress measurement was $\phi 100$ μm. Since measured stress is an average of the area in beam spots, the calculation of residual stress is given by

$$\begin{aligned}\sigma &= -\{E/2(1+\nu)\}\ \cot\ \theta_0(\pi/180)\left(\delta 2\theta_\psi/\delta\ \sin^2\psi\right)\\ &= K\left(\delta 2\theta_\psi/\delta\ \sin^2\psi\right),\end{aligned}$$

where $\sigma =$ residual stress, $E =$ Young's modulus, $\nu =$ Poisson's ratio, $\theta_0 =$ Bragg's diffraction angle of determined crystallographic plane of stress-free sample of the material, $\theta_\psi =$ Bragg's diffraction angle of the

Table 1
The chemical composition of the pure vanadium

	C	N	O	H	Al	Cr	Cu	Fe	Si	V
Content (wt. ppm)	14	23	60	12	360	25	18	550	30	bal.

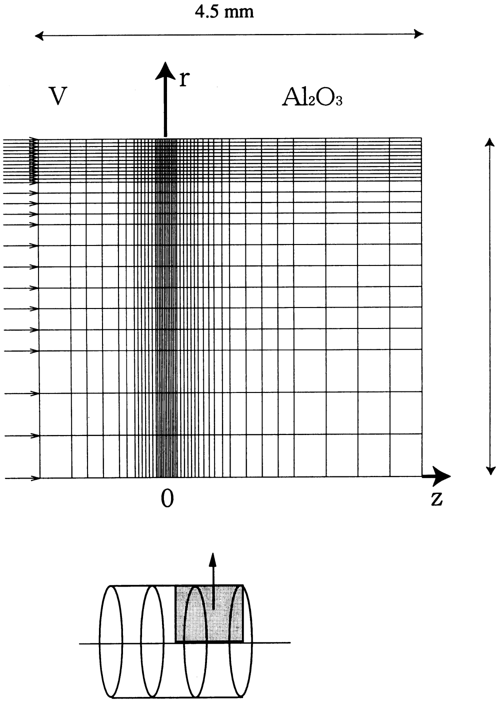

Fig. 2. The axi-symmetric quadrilateral elements of the modeled area for FEM analysis.

determined crystallographic plane of the material under study as a function of ψ angle, ψ = the angle of determined crystallographic plane to material's measured surface, and K is constant [13].

In this work, strain in alumina was measured by strain of $(1\ 4\ \bar{5}\ 6)$ plane ($\theta_0 = 136.08$) as a function of ψ angle (0°, 16°, 20°, 30°, 40°, 50°).

3. Results and discussion

3.1. FEM analysis

Fig. 4 shows the results of FEM analysis. Fig. 4(a) shows the enlargement of the stress concentrated area at the outer surface of the boundary of the joint. In Fig. 4(b) and (c), the residual stress distribution is shown as the gradation of the black/white contrast. The white area shows the area loaded by higher tensile stress and the dark area shows the area loaded by lower tensile stress or compressive stress.

Fig. 4(b) shows the radial stress (σ_{rr}) distribution, and Fig. 4(c) shows the vertical stress (σ_{zz}) distribution of the same area. Both of them show the highest tensile stress concentrated at the outer surface of the boundary of the joint. The maximum of radial tensile stress (σ_{rr}) is about 364 MPa and that of vertical tensile stress (σ_{zz}) is about 565 MPa in the alumina. Compressive stress is observed in the vanadium layer near the tensile stress concentrated area. It might be due to the effect of yielding of the vanadium. In the other area, out of the figure, there was no significant stress or stress distribution.

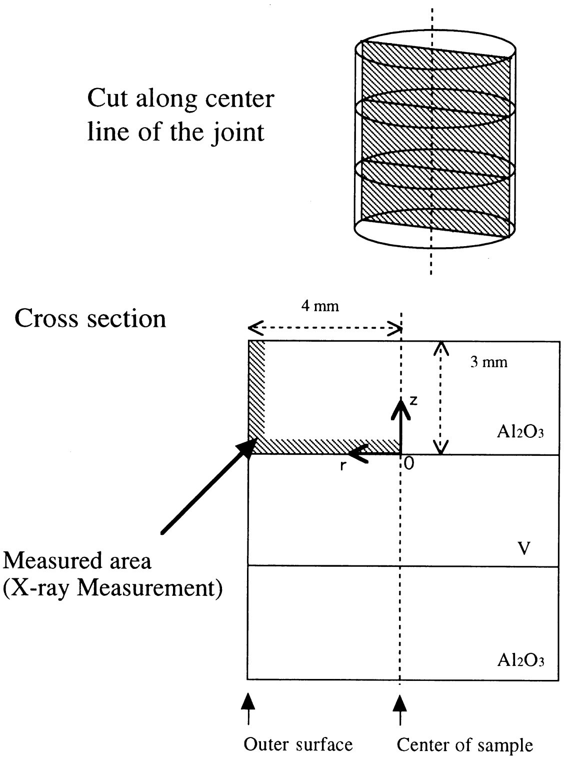

Fig. 3. X-ray stress measurement was done in the area of the cross-section of the alumina layer of the joint.

3.2. X-ray stress measurement

Figs. 5 and 6 show the results of X-ray stress measurement and residual stress distribution in vanadium/alumina joint, respectively. The error bars along the x-axis show the width of X-ray beam spots, and the error bars along y-axis show the errors of X-ray stress measurement results that depend on statistical errors of $2\theta_\psi$ data as function of ψ angle. The residual stress measurements are done in the area of the alumina along the jointing boundary and outer surface. The area width are shown in each figures ($0 < z < 200$ (400) or 3500 (3700) $< r < 4000$), which depend on the width of the beam spots. Since the X-ray beam spots are elliptic, and longer along the measured stress direction, the area width are deferent in radial and vertical stress direction. Fig. 5 shows the residual stress distribution of the area in the alumina layer along the boundary of the joint. The

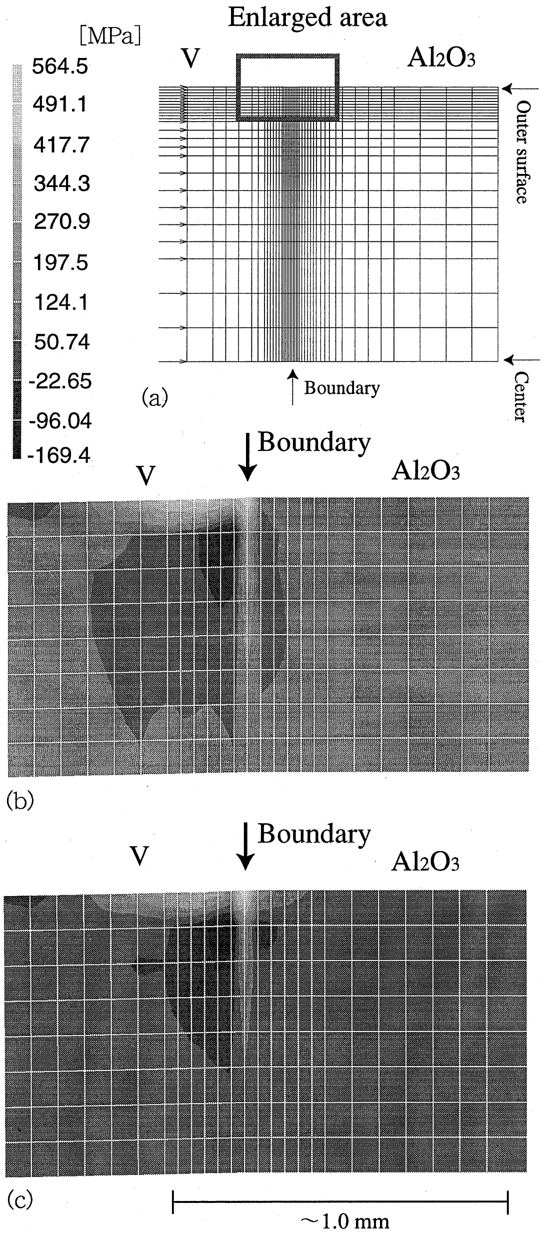

Fig. 4. The FEM analyzed results of the stress concentrated area: (a) Explain about the enlarged area; (b) Radial stress σ_{rr} distribution; (c) Vertical stress σ_{zz} distribution.

x-axis shows the distance from the center line of the joint, and the y-axis shows the measured residual tensile stress. Fig. 5(a) shows the radial tensile stress (σ_{rr}) distribution, and Fig. 5(b) shows the vertical tensile stress (σ_{zz}) distribution.

In Fig. 5(a), there is the highest radial tensile stress (about 330 MPa) at the outer surface of the joint. The minimum residual stress (about 0 MPa) was observed at

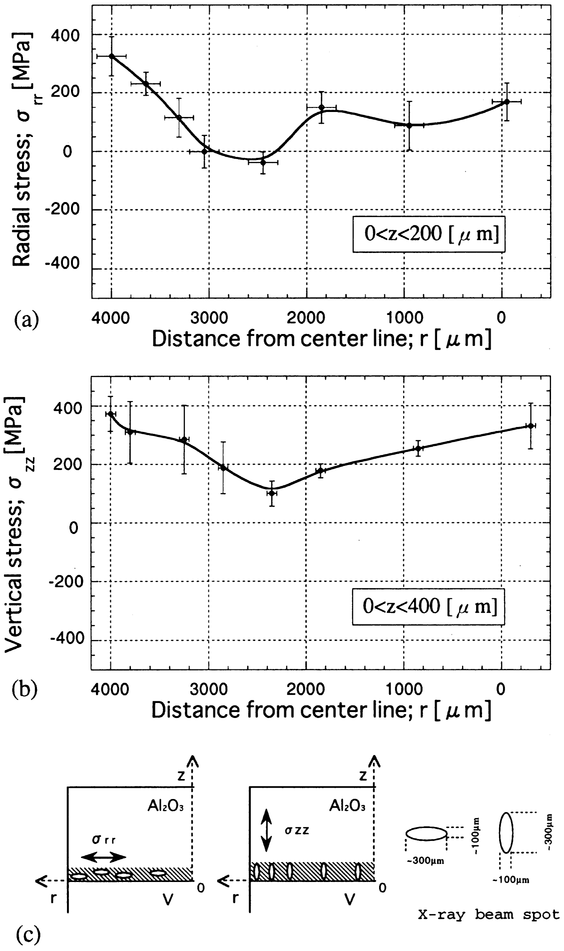

Fig. 5. The result of X-ray stress measurement along the boundary, in hatched area in (c). (a) Radial tensile stress σ_{rr} distribution. (b) Vertical tensile stress σ_{zz} distribution. (c) Explain about the measured area.

the place of $r = 2350$ μm. And there are tensile stresses in the center area of the joint. These tensile stresses are not found in FEM analyzed results.

Vertical stress distribution of the same area is shown in Fig. 5(b). There is the highest vertical tensile stress (about 370 MPa) at the outer surface of the joint. And there is minimum tensile stress (about 100 MPa) at the place of $r = 2350$ μm, the same place that the minimum radial stress was observed, and there are vertical tensile stresses in the center area of the joint.

Fig. 6 shows residual stress distribution in the area along the outer surface of the joint. The x-axis shows the distance from the jointing boundary of the joint, and the y-axis shows the measured residual tensile stress. Fig. 6(a) shows radial tensile stress (σ_{rr}) distribution, and Fig. 6(b) shows vertical tensile stress (σ_{zz}) distribution.

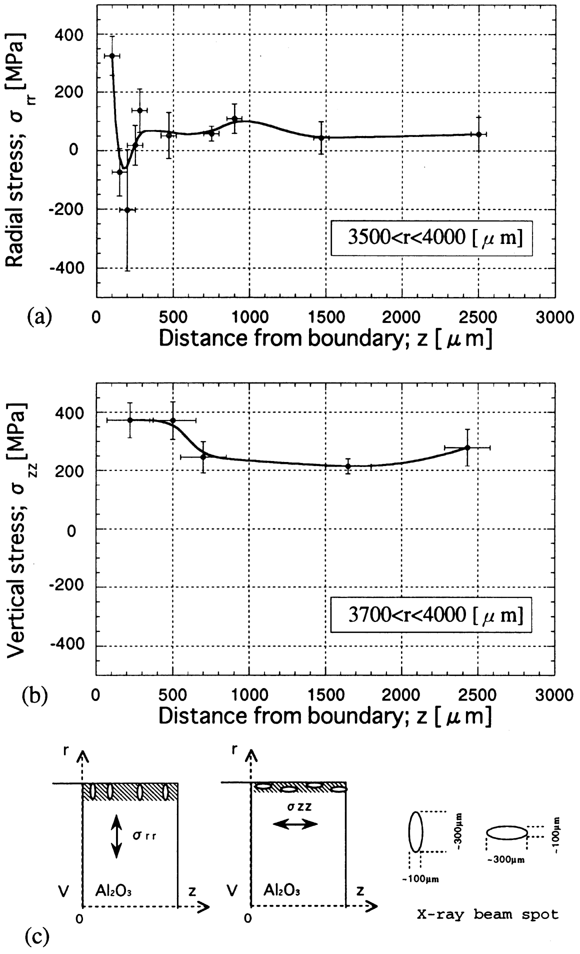

Fig. 6. The result of X-ray stress measurement along the outer surface, in hatched area in (c). (a) Radial tensile stress σ_{rr} distribution. (b) Vertical tensile stress σ_{zz} distribution. (c) Explain about the measured area.

Both of them show that the highest tensile stress appears at the boundary of the joint. In Fig. 6(a), complicated stress distribution shape near the boundary is shown.

3.3. Stress distribution and crack formation

FEM analysis and X-ray stress measurement provide us with the residual stress distribution of the vanadium/alumina joint. Both the results show that the highest tensile stress appeared at the outer surface of the boundary of the joint. The residual stress may cause cracks in joint, or failure of bonding.

The results of FEM calculation and X-ray measurement did not agree as follows: (1) The FEM analyzed result of stress distribution show steeper shape than the result of X-ray stress measurement. One of the reason of the deference might be that the X-ray measured stress is the average stress in the area of the X-ray beam spot. Thus the shape of X-ray measured stress distribution became gentle. (2) The second deference is that there is the tensile stress obtained by X-ray stress measurement in the center area of the joint, but it is not obtained in the result of FEM analysis. It would be able to consider the reason in two ways. The one is that there was already residual tensile stress in the alumina before bonding. Actually, by X-ray stress measurement, there was tensile stress (50–100 MPa) obtained in the same area of the alumina, cut off from the same rod of the material of the joint, but never bonded, and heat-treated as same as bonding heat treatment. The second considerable reason is the stress redistribution effect of cutting the joint sample. X-ray stress measurement was done on the cross-section of the joint after cutting along the center line of the joint, but FEM analysis was done as the joint was never cut. Cutting the joint, the residual stress distribution along the perpendicular direction to the cross-section would be changed. It might cause some change of the stress distribution on the cross-section by the effect of Poisson's ratio.

And there are also some other considerable reasons of the disagreement of the results of FEM analysis and X-ray stress measurement. For example, in FEM analysis, the joint supposed bonded at 1400°C and cooled to 25°C, but it is not certain at what temperature the real joint was bonded during the heat treating process. Bonded at a lower temperature, below 1400°C would be possible.

Anyway, both the results obtained by FEM analysis or X-ray stress measurement show the same trend of stress distribution and the highest tensile stress concentration at the outer surface of the boundary of the joint. Fig. 7 shows the schematic illustration of the cross-section of joint bonded at 1500°C [8]. There are cracks along the boundary in the alumina layer of the joint. It indicates that the thermal stress appeared the highest at

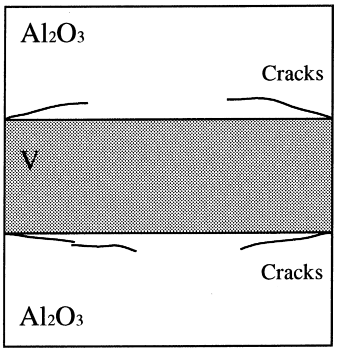

Fig. 7. Cracks along the boundary of the joint bonded at 1500°C [8].

the outer surface of the boundary of the joint. It is in accordance with the results of FEM analysis and X-ray stress measurement. When the concentrated stress becomes higher than the fracture strength of the alumina, it will cause the cracks. The fracture stress of alumina depends on details of the microstructure such as location, size and shape of pores, grain size, and the presence and location of second phases, as well as on the temperature [14]. However the bond strength of the alumina used in this work is about 200 MPa. The results of this work, FEM analysis and X-ray stress measurement, are useful to analyze the fracture process of the alumina/vanadium joints.

In order to obtain the good bonded joints without cracks, the highest residual stress in the alumina of the joint must be lower enough than the fracture strength of the alumina. There are several ways to reduce residual stress. For example, bonding at the temperature close to the temperature at which the joint will be used, would be able to reduce the thermal stress, and constrained cooling procedure for the elimination of residual stress would be effective, if the bonding temperature, the cooling temperature and the using temperature are optimized [5] or change the shape of joints, or may reduce the stress concentration. Especially, the shape of the outer surface of the joint is effective on the stress concentration rate [6]. The porosity in the metal would be able to reduce the residual stress in joint [7], but it is not sure to be available to be used for the vanadium, as structural material of fusion reactor. The inserting soft metal interlayer to the boundary of the joint or brazing would be able to reduce the residual stress in the joint [4]. Reduced activation and irradiation response of brazing such as swelling and embrittlement will be solved by inserting another material in the joint.

4. Summary

Residual stress distribution in vanadium/alumina joint was obtained by FEM analysis and X-ray stress measurement. Both the results show that the highest tensile stress is concentrated at the boundary of the outer surface of the joint, and it will cause cracks in alumina layer. Reducing the residual stress and avoiding the stress concentration is needed to obtain the soundness of the joint, and it will be used in fusion reactor system. Bonding at lower temperature or changing the shape of joints are proposed.

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