Solid State Bonding of Graphite to S45C Steel[†]

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Graphite was bonded to S45C steel by using a RF-induction furnace, and bending strength, microstructure and concentration profile of carbon of graphite/S45C steel joint were investigated. Thermal stress induced in the joint was estimated by an X-ray stress analysis and a finite element method. On the basis of these results the influence of thermal stress on the bending strength of the joint was examined in connection with the diffusion of carbon atoms.

Austenite phase contributes greatly to solid-state bonding of the graphite/steel system. Therefore good diffusion bonding becomes feasible when joining temperature exceeds eutectoid transformation temperature A_1 . Axisymmetric thermoelastic finite element analysis suggests that the increase in carbon concentration near the joining interface of S45C steel has no influence on the maximum tensile stress induced on the surface of graphite. Bending strength of the joint increases with decreasing residual thermal stress on the surface of graphite. Relaxation of thermal stress is increased to a maximum when the amounts of carbon atoms that diffuse into S45C steel reach an optimum value. Point defects introduced in graphite during annealing seem to be pertinent to thermal stress relief.

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I. Introduction

Graphite and C/C composites have excellent electrical conductivity, thermal conductivity, heat resistance, thermal shock resistance, lubrication, corrosion resistance and bioaffinity, and also are light weight. Thus they are utilized as electrical, electrochemical, high temperature, bearing, wear resistant, nuclear fusion reactor, chemical reaction device, aero-space plane materials and biomaterials. However, hybrid structures in which graphite or C/C composites are combined with metallic materials are generally adopted for various devices and machinery since graphite and C/C composites are brittle. Hybridization is usually performed by mechanical joining. Brazing is also employed in the manufacture of nuclear fusion reactors⁽¹⁾.

Recently, the joining technology of dissimilar materials which uses the joining method with insert materials such as brazing or the direct joining method has been developed. Also, fundamental and application data on the joining of metal to oxide, nitride and carbide ceramics have been collected⁽²⁾. However, few studies have examined the joining of graphite or C/C composites to metal. If the excellent characteristics of both graphite or C/C composites and metal are maintained by a joining method, new prospects can be offered for development of various devices and machinery with high efficiency. The purpose of the present study is to obtain a fundamental knowledge of the direct solid-state bonding of

graphite to a carbon steel.

Essential problems in solid-state bonding are summarized in (1) bonding strength at joining interface and (2) thermal stress⁽³⁾. In problem (1), the interfacial strength may be high due to diffusion bonding because carbon is a constituent of both graphite and carbon steel. However, carbon concentration near the joining interface of carbon steel is varied by diffusion of carbon from graphite to carbon steel. Thus, the thermal stress may be influenced by the resulting microscopic changes in the thermal expansion coefficient and the modulus of elasticity. And also lattice defects may be introduced in the graphite during annealing, resulting in a change in the thermal stress. As mentioned above, it is thought that diffusion of carbon plays an important role in the problems (1) and (2). Therefore, we focused our attention on carbon diffusion in the present study.

II. Experimental Method

As test materials, a graphite rod of 99.9999 mass% and an S45C steel rod were used. The joining specimen was column 5 mm in diameter and 25 mm in length. The joining surface of the steel was finished using 1 μ m alumina polishing and that of the graphite was finished using #3000 emery paper grinding.

Figure 1 shows a schematic diagram of the joining system. The graphite and S45C steel were set first in the center of the RF-induction coil as shown in Fig. 1. Bonding was performed under a compressive stress of 6.92 MPa in a vacuum of 1×10^{-4} Pa in a temperature range from 973 to 1223 K. Residual thermal stress on the surface of the graphite of the joint was examined by X-ray stress analysis. The measurement was performed using XRD-6000

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Fig. 1 Schematic diagram of the joining system using RF-induction furnace.

(Shimazu Co.) at an acceleration voltage of 40 kV, electrical current of 40 mA and slit width of 0.2 mm. The fracture stress of the joint (a rod of 5 mm in diameter and 50 mm in length) was then measured by the four-point bending test (distance between the upper fulcrums: 10 mm, distance between the lower fulcrums: 30 mm). The microstructure of the longitudinal cross section traversing the joining interface was observed using an optical microscope and a scanning electron microscope. The longitudinal cross section was first polished with a 1 μm diamond and then ultrasonically cleaned for at least 10 min. The carbon concentration near the joining interface was then measured by CK α -ray line analysis using an electron probe micro-analyzer, JXM-8621MX (JEOL). The line analysis was performed at an acceleration voltage of 15 kV, a sample current of 0.3 μA , and a feed speed of 1.67 $\mu\text{m/s}$.

In order to examine the influence of thermal stress on the strength of the joint, thermal stress induced by cooling from the joining temperature to room temperature was calculated by the axisymmetric thermoelastic finite element analysis. The general-purpose program ANSYS was used for this analysis. **Figure 2** shows the schematic element division of the axisymmetric model (element number: 15087). Concentration of the thermal stress on the surface near the joining interface resulted in fine division of elements near the joining interface. Because a tilting concentration profile of carbon was observed near the joining interface of S45C steel, the region from the joining interface to a 1 mm depth was divided into 10 equal layers of 100 μm thickness and carbon distribution in each layer was assumed to be uniform. The thermal expansion coefficient necessary for thermal stress analysis was determined from the differential thermal expansion

Fig. 2 Schematic illustration of axisymmetric thermoelastic finite element analysis.

curve which was obtained by heating a specimen of 5 mm in diameter and 20 mm in length from room temperature to 1223 K at a heating rate of 0.25 K/s in Ar gas using a differential thermal analyzer tma8310 (RIGAKUDENKI Co.). Alumina was used as a reference material.

III. Results and Discussion

1. The bending strength of the joint

Graphite/S45C steel couples were annealed for 600 s at various temperatures which were decided at regular intervals of 50 K from 973 to 1223 K. As a result, it was hard to join graphite to S45C steel at 973 K lower than the eutectoid transformation temperature in iron-cementite system (A_1 : 1000 K). On the other hand, good joints were obtained at temperatures higher than 1023 K, that is, at temperatures higher than A_1 . This suggests that austenite participates in solid state bonding. When S45C steel is heated at a temperature lower than A_1 , the microstructure is composed of ferrite and pearlite. According to the equilibrium phase diagram of the iron-carbon system⁽⁴⁾, the solubility of carbon in ferrite is extremely low. The maximum solubility in the iron-graphite and iron-cementite systems is 0.021 and 0.022 mass%, respectively. Therefore, when the majority of the microstructure is occupied by ferrite, it is difficult to obtain good diffusion bonding of graphite to carbon steel. This likely explains that a joint could not be obtained at 973 K. On the other hand, the microstructure of S45C steel is composed of ferrite and austenite in a temperature range from A_1 to A_3 , whereas it is only composed of austenite at temperatures higher than A_3 . According to the phase

diagram, the solubility of carbon in austenite is greater than that in ferrite. Therefore, when the graphite/S45C steel couple is heated to a temperature at which austenite exists in the microstructure of S45C steel, diffusion bonding may be possible due to remarkable diffusion of carbon atoms from graphite to austenite. This explains why good joint was obtained at temperatures higher than A_1 .

Figure 3 shows the relationships between bending strength of the joints and the joining conditions. The bending strength of graphite showed little change even when annealed at 1223 K. Dashed line in Fig. 3 shows the bending strength of monolithic graphite. The bending strength of the joint at 1073 K increased with holding time, reaching that of monolithic graphite at 2400 s. At 1123 K, the bending strength of the joint increased initially with holding time, but decreased when the time exceeded 1800 s. The bending strength at 1223 K was increased a maximum at 300 s, decreased gradually with holding time. As mentioned above, the holding time at which the bending strength shows the highest value shifts to shorter

Fig. 3 Relationship between the bending strength of graphite/S45C steel joints and joining conditions. The dashed line shows the bending strength of graphite.

Fig. 4 Scanning electron micrograph of the interface of graphite/S45C steel joint bonded by annealing at 1223 K for 300 s.

time as the joining temperature increases. In the bending test, the fracture occurred in graphite near the joining interface in every case. This suggests that bonding at the interface is strong.

Figure 4 shows the scanning electron micrograph of the longitudinal cross section traversing the joining interface of the joint bonded at 1223 K for 300 s. A black part of the left side shows graphite, and a white part of the right side S45C steel. No voids were found at the joining interface. Therefore, strong bonding at the graphite/S45C steel interface may be expected. Because irregularity is observed at the joining interface in Fig. 4, it is thought that anchor effect contributes to a rise of the bonding strength. Thus, it may be said that the problem (1) in solid-state bonding is solved.

2. Relationship between strength of the joint and thermal stress

In the bending test, the fracture occurred near the joining interface in the graphite. Furthermore the bending strength of the joint varied according to joining conditions, as shown in Fig. 3. This suggests that the strength of the joint is influenced by thermal stress. Thermal stress analysis by the finite element method showed that a maximum tensile thermal stress was located at a distance of 1.2 mm from the joining interface on the surface of the graphite. Therefore, we measured residual thermal stress at this position by X-ray stress analysis. **Figure 5** shows a comparison of the residual stress measured by X-ray stress analysis, σ_{zX} , with the difference between the bending strength of monolithic graphite and that of the joint, σ_{zR} (Fig. 3). The value of σ_{zR} showed good agreement with that of σ_{zX} . This suggests that the strength of graphite in the joint was degraded, depending on the magnitude of residual tensile stress. Thus, σ_{zR} represents the residual thermal stress on the surface of graphite.

The thermal stress is related to the difference between room temperature and the joining temperature and physi-

Fig. 5 Comparison of residual stress measured by X-ray stress analysis, σ_{zX} , with a difference between the bending strength of graphite and that of graphite/S45C steel joint, σ_{zR} .

cal properties (thermal expansion coefficient, modulus of elasticity and Poisson's ratio). As shown in Fig. 3, however, the magnitude of residual thermal stress varied with holding time even when the graphite/S45C steel couples were annealed at the same temperature. In annealing at elevated temperature, carbon concentration near the joining interface in S45C steel varies according to the diffusion of carbon atoms from graphite to S45C steel. This change may accompany microscopic changes in the physical properties, resulting in changes in the thermal stress.

3. Concentration profile of carbon near the joining interface in S45C steel

Figure 6 shows the optical microstructure of the longitudinal cross section of the joint obtained by annealing at 1223 K for 600 s. A black part of the left side shows graphite, and the right side shows S45C steel. No Fe_3C layer was found at the joining interface. In S45C steel, the microstructure consisted of a hyper-eutectoid structure (network of cementite and pearlite) near the joining interface, a eutectoid structure (only pearlite) at the center of Fig. 6 and a hypo-eutectoid structure (ferrite and pearlite) at the right side of Fig. 6. Thus, carbon concentration decreases with the distance from the joining interface. Carbon atoms diffused into the inner region and the concentration gradient of carbon decreased with increasing holding time, though the microstructure near the joining interface was almost unchanged. In the case of annealing at 1073 and 1123 K, the microstructure near the joining interface was composed of pearlite and a network of cementite. However, the amount of such cementite was smaller at 1073 K than at 1123 K. These results suggest that carbon concentration near the joining interface decreases with a decrease in joining temperature. This is closely related to that the solubility of carbon in austenite decreases with a decrease in temperature as shown in the

Fig. 6 Optical microstructure of longitudinal section of graphite/S45C steel joint bonded by annealing at 1223 K for 600 s.

phase diagram⁽⁴⁾.

In order to examine exact concentration profile of carbon near the joining interface, CK α -ray line analysis was performed using an electron probe micro-analyzer on the longitudinal cross section of S45C steel bonded to graphite at 1223 K for 120 s, followed by water quenching, that is, martensitization. Figure 7 shows the result of CK α -ray line analysis with a beam of 1 μm in diameter. It is usually believed that the information obtained actually is taken from an area of approximately 10 μm even when a beam is 1 μm in diameter. Thus, information from both sides of the joining interface is detected as the beam approaches the joining interface. Figure 7 shows the carbon profile in a region where carbon intensity is not influenced by graphite. By extrapolating this profile to the joining interface, $z=0$, the intensity of CK α -ray at the joining interface was estimated to be 1400 s^{-1} . Figure 8 shows the calibration curve determined by CK α -ray line analysis under the same analytical conditions as those indicated in Fig. 7. Quenched carbon steels with

Fig. 7 CK α -ray line analysis of longitudinal section of graphite/S45C steel joint bonded by annealing at 1223 K for 120 s.

Fig. 8 Calibration curve for the estimation of carbon content.

Fig. 9 Temperature dependence of diffusion coefficient.

known carbon content were used as the reference. From this calibration curve, the carbon concentration at the joining interface shown in Fig. 7 was estimated to be 1.4 mass%. This value agrees with the solubility of carbon in austenite at 1223 K in the iron-graphite phase diagram⁽⁴⁾, 1.4 mass%. Based on the CK α -ray line analysis and metallographical analysis, the carbon concentration at the joining interface during heat treatment for joining may be related to the solubility of carbon in austenite in the iron-graphite phase diagram.

Next, we examined the change in carbon concentration near the joining interface depending on the bonding conditions. Assuming diffusion of carbon atoms in austenite under non-steady state conditions, the carbon concentration near the joining interface can be obtained by solving Fick's second law⁽⁵⁾ under the boundary conditions that the initial carbon content is 0.45 mass% and the carbon concentration at the joining interface is the solubility limit of carbon in austenite. The carbon concentration is given by

$$C = 0.45 + (C_1 - 0.45) \{1 - \operatorname{erf}(z/2\sqrt{Dt})\} \quad (1)$$

where z is the distance from the joining interface, C is the carbon concentration (mass%) at point z , C_1 is the carbon concentration (mass%) at the joining interface, D is the diffusion coefficient of carbon, which is independent of carbon concentration, t is the holding time and erf is Gauss's error function. Substituting the distance from the joining interface to eutectoid concentration (0.76 mass% in the phase diagram⁽⁴⁾) in eq. (1), the value of D at each temperature can be obtained. The temperature dependence of D is given by the following equation:

$$D = D_0 \exp(-Q/RT) \quad (2)$$

where D_0 is the frequency factor, Q is activation energy for carbon diffusion in austenite, T is the joining temperature and R is the gas constant. Figure 9 shows logarithm of D vs. $1/T$ plots. A proportional relationship defined by eq. (2) holds between these two factors shown in Fig. 9. The values of $D_0 = 1.12 \times 10^{-5} \text{ m}^2/\text{s}$ and $Q = 119 \text{ kJ/mol}$ were obtained from the y-intercept and the slope of the straight line, respectively. These values are almost identical to the values reported for volume diffusion,

$D_0 = 1.5 \times 10^{-5} \text{ m}^2/\text{s}$, $Q = 136 \text{ kJ/mol}$ ⁽⁶⁾.

Figure 10 shows the concentration profiles of carbon for 2 cases. One of the curves was obtained by substituting the values of D_0 and Q in eq. (1), while another one was determined quantitatively through calibration (Fig. 8) of CK α -ray profile (Fig. 7). The curves showed good agreement. This suggests that the concentration profile of carbon can be expressed by eq. (1). The concentration profile of carbon obtained from eq. (1) are shown in Fig. 11. Figure 11(a) shows the change in carbon profile with holding time. Carbon atoms diffused into deeper region, and the concentration gradient became moderate with an increase in holding time. This was confirmed by metallographic analysis. Figure 11(b) shows the change in concentration profile of carbon with joining temperature. Although carbon concentration at the joining interface varied with joining temperature, the shape of the curve did not change. The changes of carbon concentration and concentration profile of carbon generally accompany changes in the thermal expansion coefficient, modulus of elasticity and strength.

Fig. 10 Distribution of carbon concentration near the interface of graphite/S45C steel joint bonded by annealing at 1223 K for 300 s. The chain, solid and dashed lines are calculated from eq. (1), obtained from CK α -ray line analysis and extrapolated to the interface, respectively.

Fig. 11 Variation of concentration profile of carbon with joining conditions.

4. Carbon content dependence on the thermal expansion coefficient and modulus of elasticity

The differential thermal expansion test revealed that the thermal expansion coefficient of graphite is $6.79 \times 10^{-6} \text{ K}^{-1}$, independent of temperature. On the other hand, thermal expansion of carbon steel depends on the carbon content because carbon steel demonstrates remarkable shrinkage at A_1 . Thus, the differential thermal expansion tests were conducted by using three reference carbon steels with different carbon content (0.45, 0.83 and 1.60 mass% C) to examine the relationship between carbon content and the thermal expansion coefficient. In the present study, the mean thermal expansion coefficients were calculated in the ranges of room temperature to desired temperatures. Figure 12 shows the change in the mean thermal expansion coefficient with carbon content. The mean thermal expansion coefficient increased linearly with carbon content. This relationship can be expressed by

from room temperature to 1073 K

$$\alpha = 1.30 \times 10^{-5} + 1.21 \times 10^{-6} C \quad (3)$$

from room temperature to 1123 K

$$\alpha = 1.35 \times 10^{-5} + 1.61 \times 10^{-6} C \quad (4)$$

Fig. 12 Change in the mean coefficient of thermal expansion with carbon content.

from room temperature to 1223 K

$$\alpha = 1.38 \times 10^{-5} + 2.42 \times 10^{-6} C \quad (5)$$

where α is the mean thermal expansion coefficient and C is the carbon content (mass%). The mean thermal expansion coefficient at any carbon content can be determined from these equations.

The modulus of elasticity in carbon steel decreases linearly with increasing fraction of cementite or carbon content⁽⁷⁾. This relationship is represented by the following equation:

$$E_s = 212.7 - 6.86C \quad (6)$$

where E_s is the modulus of elasticity (GPa) of carbon steel and the constant 212.7 (GPa) is the coefficient of elasticity in ferrite. The modulus of elasticity at any carbon content can be determined from this equation. Poisson's ratio of carbon steel is 0.28⁽⁸⁾, independent of carbon content. The modulus of elasticity and Poisson's ratio of the graphite used in the present study were 6.72 GPa and 0.30, respectively.

5. Thermal stress analysis by finite element method

The influence of carbon concentration on thermal stress was examined by axisymmetric thermoelastic finite element analysis. For the purpose, a region from the joining interface to 1 mm depth was equally divided into 10 layers. Substituting the distance from the joining interface to the center of each layer in eq. (1), the mean carbon content of each layer can be determined. When this value is substituted into one of eqs. (3) to (5) and (6), the mean thermal expansion coefficient and modulus of elasticity of each layer can be obtained.

Figure 13 shows the longitudinal thermal stress distribution on the surface of the joint bonded by annealing at 1123 K for 300 s. The longitudinal stress was almost identical to the principal stress (data not shown). Figure 13(a) shows the stress distribution near the joining interface, and Fig. 13(b) shows an enlarged picture of the graphite side. Tensile stress was induced in the graphite, whereas compressive stress was induced in S45C steel. This is likely because the thermal expansion coefficient of graphite is

Fig. 13 Thermal stress distribution on the surface of graphite/S45C steel joint bonded by annealing at 1123 K for 300 s. σ_{zF} shows longitudinal stress calculated with a finite element method.

smaller than that of the steel. As shown in Fig. 13(b), the maximum tensile stress is located at a distance 1.2 mm from the joining interface. This position was almost unchanged even when the holding time was varied. The analytical results at 1073 K were similar to those at 1123 K. **Figure 14** shows the analytical results at 1223 K. Tensile stress was induced in S45C steel as well as in graphite. In heating to 1223 K, carbon concentration near the joining interface of S45C steel is raised to the higher solubility, as mentioned above. As a result, the thermal expansion coefficient near the joining interface was larger than that of graphite and S45C steel. The tensile thermal stress in S45C steel is thought to be due to the marked increase in carbon concentration near the joining interface. The maximum tensile stress in graphite at 1223 K was larger than that at 1123 K. However, the position of maximum tensile stress remained almost unchanged regardless of joining temperature. This position was independent of holding time at 1123 and 1223 K. In the bending test, the position of fracture corresponded approximately to that of maximum tensile stress. This suggests that the bending strength of the joint is closely related to the thermal stress.

As mentioned above, the difference between the bending strength of monolithic graphite and that of the joint

Fig. 14 Thermal stress distribution on the surface of graphite/S45C steel joint bonded by annealing at 1223 K for 300 s.

represents the residual thermal stress on the surface of graphite of the joint. **Figure 15** shows the changes in the maximum longitudinal stress calculated by the finite element method, σ_{zFMAX} , and residual thermal stress, σ_{zR} , according to the joining conditions. σ_{zFMAX} increased with increasing joining temperature. This is likely due to a more pronounced difference in the temperature and increase in the mean thermal expansion coefficient (Fig. 12). However, σ_{zFMAX} was independent of holding time as shown in Fig. 15. This suggests that changes in carbon concentration near the joining interface do not influence the maximum longitudinal stress on the surface of the graphite. σ_{zR} shows good agreement with σ_{zFMAX} under the joining conditions of the short annealing time at 1073 and 1123 K and also the long annealing time at 1223 K. However, σ_{zR} was smaller than σ_{zFMAX} under the other joining conditions. This suggests that thermal stress is released by some action during this bonding process.

6. Relaxation of thermal stress

A large compressive stress is generated near the joining interface, as shown in Figs. 13 and 14. As one of factors of thermal stress relaxation, plastic deformation of the S45C steel due to this compressive stress may be predicted. The maximum compressive stresses near the joining interface in Figs. 13 and 14 were 300 and 450 MPa, re-

Fig. 15 Changes in the maximum longitudinal stress on the surface of graphite, σ_{zFMAX} , and σ_{zR} with joining conditions.

spectively. As mentioned above, the carbon concentration near the joining interface was estimated to be 1.04 and 1.4 mass%, respectively. The corresponding yield stresses were 686 and 657 MPa, respectively⁽⁹⁾. Because the maximum compressive stress calculated by the finite element method was smaller than the yield stress, relaxation of thermal stress does not appear to be due to plastic deformation of the carbon steel.

We examined the relaxation of thermal stress due to deformation of graphite. Graphite is hexagonal and anisotropic, that is, it has a directional variation in structure and properties. The strong covalent bonds within the basal planes retain this crystalline solid to more than 2500 K, while the weak Van der Waals bonds between the basal planes permit graphite layers to slide by one another when sheared. Thus, when joining is conducted at an elevated temperature, point defects may be introduced between the basal planes near the joining interface of the graphite since diffusion of carbon atoms into austenite or interstitial diffusion occurs readily compared

to self-diffusion of iron. This is caused by the directional difference in self-diffusion rate of carbon due to anisotropic properties. Although no voids exist near the joining interface of the graphite in Fig. 4, large amounts of point defects may be formed near the joining interface of the graphite. The amount of carbon atoms that diffuse into S45C steel can be estimated by the following method. Assuming that the carbon concentration is maintained at C_1 in the region from the joining interface to a depth z_m , eq. (1) follows:

$$z_m = 1.1 \sqrt{Dt} \quad (7)$$

Thus, the amount of carbon atoms that diffuse into S45C steel is given by

$$V_C = C_1 \cdot z_m = 1.1 \sqrt{Dt} \cdot C_1 \quad (8)$$

where V_C is the amount (m^3) of carbon atoms that diffuse into S45C steel. The relationship between relaxation of thermal stress and V_C is discussed here.

The difference between the calculated thermal stress and residual thermal stress represents the magnitude of relaxation of thermal stress. The ratio of relaxation of thermal stress to σ_{zFMAX} is given by the following relationship:

$$R = \left(\frac{\text{the magnitude of relaxation of thermal stress}}{\sigma_{zFMAX}} \right) \times 100 \\ = \left(\frac{\sigma_{zFMAX} - \sigma_{zR}}{\sigma_{zFMAX}} \right) \times 100 \quad (9)$$

where R is the stress relief ratio (%). Figure 16 shows the relationship between R and V_C . R increases with V_C , reaching a maximum at $V_C = 2 \sim 3 \times 10^{-6}$, and then decreases with increasing V_C . Up to V_C of $2 \sim 3 \times 10^{-6}$, point defects in graphite increase with increasing V_C . The increase in the concentration of the defect allows graphite to be deformed easily, resulting in relaxation of thermal stress. On the other hand, when V_C exceeds $2 \sim 3 \times 10^{-6}$, diffusion of iron into graphite as well as diffusion of carbon into steel occurs readily due to large amounts of point defects in graphite, resulting in a decrease in point defects in graphite. Therefore, the relaxation of thermal stress is lowered as V_C exceeds

Fig. 16 Relationship between stress relief ratio R , that is, $(\sigma_{zFMAX} - \sigma_{zR}) / \sigma_{zFMAX}$ and the amount of carbon atoms which diffuse into S45C steel, V_C .

$2 \sim 3 \times 10^{-6}$. Thus, the marked relaxation of thermal stress at $V_C = 2 \sim 3 \times 10^{-6}$ is thought to be due to the large amounts of point defects in graphite. At a lower joining temperature, a long time is required to reach V_C of $2 \sim 3 \times 10^{-6}$. On the other hand, at a higher joining temperature, this condition is achievable much more quickly. This likely explains why the joint attains the maximum bending strength under annealing at 1073 K for 2400 s or at 1223 K for 300 s.

IV. Conclusions

Graphite was bonded to S45C steel in the solid state, and the bending strength of the joint, microstructure and concentration profile of carbon near the joining interface were investigated. The thermal stress induced in the joint was estimated by X-ray stress analysis and the finite element method. Based on these results, the influence of thermal stress on the bending strength of the joint was examined in connection with the diffusion of carbon atoms. The conclusions obtained are as follows:

(1) The austenite phase contributes greatly to solid state bonding in the graphite/steel system. Thus, accomplishing good diffusion bonding is difficult at temperatures lower than the eutectoid transformation temperature A_1 . It becomes feasible when the joining temperature exceeds A_1 .

(2) A large tensile thermal stress is induced on the surface near the joining interface of graphite. Axisymmetric thermoelastic finite element analysis revealed that the maximum tensile thermal stress induced on the surface of

graphite increases with increasing joining temperature, whereas the concentration profile of carbon near the joining interface of S45C steel had no influence on the maximum tensile thermal stress.

(3) A comparison of the thermal stress calculated by the finite element method with the residual thermal stress revealed that some thermal stress is released on the graphite side. In addition, the bending strength of the joint increases with decreasing residual tensile thermal stress on the surface of graphite.

(4) Relaxation of thermal stress is increased to a maximum when the amount of carbon atoms that diffuse into S45C steel reaches an optimum value. Relaxation of thermal stress may be related to point defects introduced in graphite during annealing.

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