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Effect of residual stress on the strength of alumina–steel joint with Al–Si interlayer

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The effect of residual stress on the strength of an alumina–steel joint with the Al–Si interlayer was studied. Alumina rods, 32 mm in diameter and 9 mm in length and steel pipes were diffusion bonded at 873 K and at a contact pressure of about 5 MPa for 30 min in a vacuum of $2 \sim 4 \times 10^{-2}$ Pa. The interlayer of aluminium sheet clad with Al–10% Si alloy on both sides was used. The tensile strength of the joints is influenced by the thickness of the interlayer or the intermetallic compound formed between the interlayer and the steel. The strength increases with increasing interlayer thickness and with decreasing intermetallic compound thickness. It is found that the residual stress measured by Sachs method is much lower than that by the elastic calculation. The stress decreases with increasing interlayer thickness. Increase in thickness of the aluminium core of the interlayer is effective in improving the joint strength. This improvement can be explained by considering the stress of the joint.

1. Introduction

Because of the growing demand of ceramics in industrial application, the attempt has been expanding into the use of ceramics in machine parts.

The use of ceramics coupled with metals is unavoidable for the purpose of compensating their own weak points. Consequently research on joining ceramics and metals has been highlighted recently and various methods have been proposed so far [1]. However there are still some problems to be solved while in establishing the reliable joining method, e.g. residual stress induced by thermal expansion mismatch, microstructure and mechanical properties of the interface and strength of ceramics itself. The stress relief of the joints during and after joining is considered to be the most difficult problem. Many studies have been taken to overcome residual stress experimentally and analytically [2, 3]. It is, however, known that the calculated stress of the joint does not always correspond to the true stress since most calculations are based on the assumption that both ceramic and metal deform fully elastically. It is, therefore, desirable to know the true stress of the joint for the design of the machine using ceramics.

The authors have developed the joining method of ceramics and metals using an Al–10% Si alloy interlayer. The interlayer acts as both stress reliever and reaction promoter and produces the reliable ceramic and metal joints having a bending strength of about 300 MPa [4, 5]. In this paper the effect of the Al–Si alloy interlayer thickness on stress relief and the strength of joint is studied. The residual stress is measured experimentally and compared with the calculation.

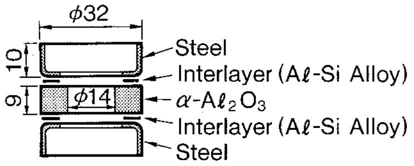

Figure 1 Shape of the specimen.

2. Experimental procedure

Figure 1 shows a shape of the specimens used in this study. Alumina of 99.7% purity, 32 mm in diameter 9 mm in thickness, and 0.06% C steel pipes are coupled as illustrated in Fig. 1. A 0.16 mm thick Al–10% Si alloy clad on pure aluminium (hereafter called the Al–Si interlayer) is inserted between the alumina and the steel pipes. Figure 2 shows the detail of the Al–Si interlayer used in this study. The Al–Si interlayer consisted of 0.14 mm thick pure aluminium sandwiched between two Al–10% Si alloy sheets (approximately 10 μm thickness). This interlayer shows melting at about 863 K for Al–10% Si and at 933 K for pure aluminium. Furthermore 0.6 mm thick pure aluminium sheet is added between the two Al–Si interlayers to control the thickness of the whole interlayer. The surface roughness of the specimens is adjusted to about $R_{\max}$ of 3 μm by grinding. After degreasing the specimen surfaces, the interlayer was inserted between the alumina and the steel pipes and they were diffusion bonded under the conditions in which the maximum strength of the joint can be obtained as shown in the previous studies [4, 5] in a vacuum of $2 \sim 4 \times 10^{-2}$ Pa. This means a pressure

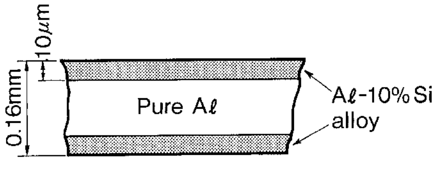

Figure 2 Detail of the Al–Si interlayer.

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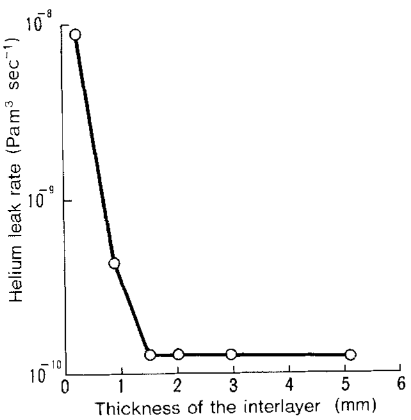

Figure 3 Helium leak rate of the joints.

of 4.9 MPa, at 883 K where only Al–10% Si layer is in the molten state and for 30 min.

Evaluations of the joints are carried out by the helium leak test and the tensile test. The helium leak test is carried out by a helium leak detector. After the helium leak test a 0.2% C steel plate (29.5 mm in diameter and 9 mm in thickness) with a tapped hole is spot welded to the pipes to consist the couplings for tensile test. Two joints joined with 0.8 mm and 2.5 mm thickness interlayers are prepared for measuring residual stress and strain gauges are attached to the alumina and the pipe near the joining interface. Strain is measured by remaining the Al–Si interlayer by cutting.

3. Results and discussion

3.1. Strength of the joint

First the helium leak test is carried out to inspect the soundness of the joints. Figure 3 shows the relationship between the helium leak rate of the joint and the thickness of the interlayer. The helium leak rate changes with the thickness of the interlayer and a helium leak rate of less than 1.3×10^{-9} Pa m^3 sec^{-1} (10^{-8} torr ℓ sec^{-1}) is obtained when the thickness of the interlayer exceeds about 0.8 mm. This result shows that very few defects such as cracks and voids are generated in the joints, when the interlayers of more than 0.8 mm thick are used.

Tensile strength of these joints is measured after the helium leak tests. The result is shown as a function of the interlayer thickness in Fig. 4. As is clear in Fig. 4, the tensile strength of the joints increases with the interlayer thickness up to about 2.0 mm and reaches at a constant value of about 23 MPa even though the interlayer thickness increases more than 2.0 mm. The fracture point of the joints is classified into three types, (a) alumina, (b) interface between alumina and Al–Si interlayer and (c) mixture of (a) and (b). It is shown that the fracture point varies with the strength of the joint and the joints showing the tensile strength of less than 17 MPa are fractured in alumina. It is, therefore, clear that the helium leak test is closely related to both strength of the joint and the fracture point indicating that the strength of the joints which are fractured in alumina is low. It should be noted that the strength of the joint measured by the tensile test is much lower than that by other tests even though the same joining is applied. The previous result measured by a four-point bending test has shown that the strength of the alumina and steel joints (10 mm in diameter and 30 mm in length) under the same joining condition was over 150 MPa [4, 5] and all the fracture points were alumina itself. When compared with the previous result, the strength of the joint in this study is extremely low and the fracture points are not always in alumina. Two reasons, the difference in the testing method and the specimen size, are considered. It is well known that the strength of materials is affected by testing method and the strength determined by bending test is generally higher than that by tensile test [6]. The effect of specimen size on the strength of the joint is also well known and it decreases with increasing of specimen size because of increasing both joining defect and residual stress in the joint [7]. It is, therefore, considered that the difference results for both test method and specimen size.

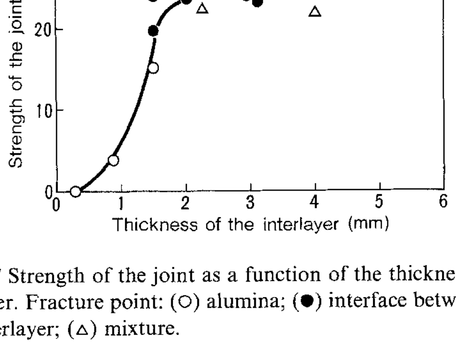

Figure 4 Strength of the joint as a function of the thickness of the interlayer. Fracture point: (○) alumina; (●) interface between steel and interlayer; (△) mixture.

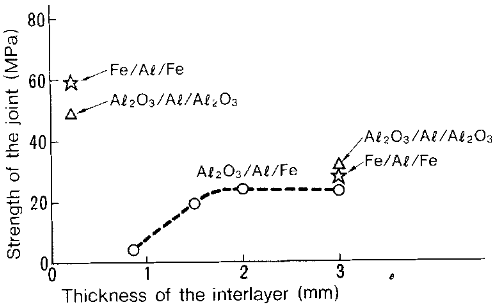

Figure 5 Relationship between strength of the steel joint and thickness of the interlayer.

In Fig. 4, the fact that almost all joints are fractured at the interface between the Al–Si interlayer and the steel may indicate that the strength of the joint is determined by the strength of the interface. This may be confirmed by the fact that the strength of the joints does not change even when the interlayer thickness increases more than 2.0 mm.

Steel pipe and joints made of steel pipe are prepared by the same method so as to know the strength of the interface between the interlayer and the steel. The strength of the steel–steel joint is shown in Fig. 5. The strength of the steel–steel joint decreases with the interlayer thickness contrary to the alumina–steel joint. The strength reaches about 60 MPa at the interlayer thickness of 0.16 mm but decreases to about 20 MPa at 3.0 mm. As is clear in Fig. 5, the strength of

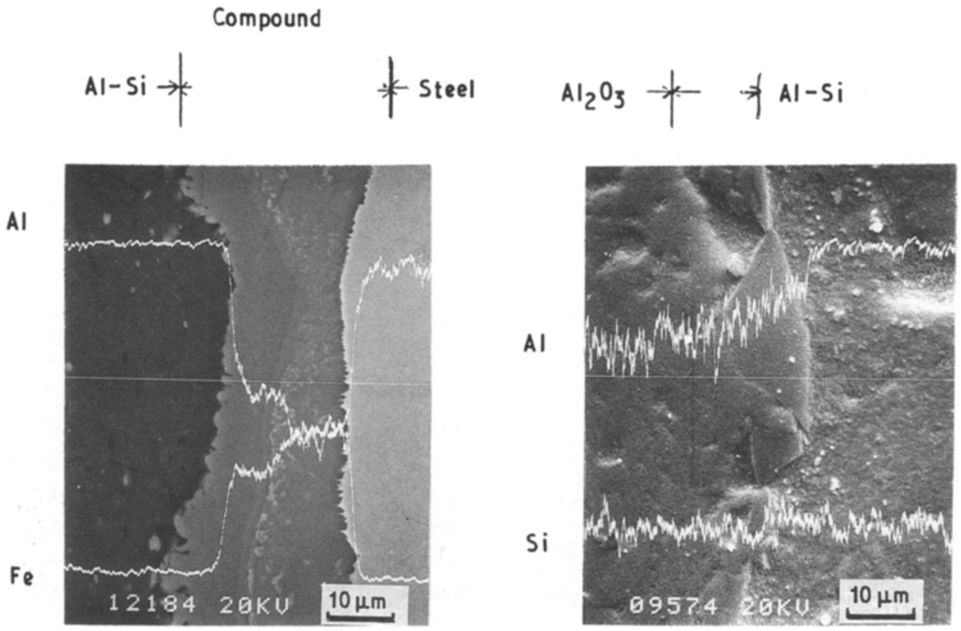

Figure 6 Scanning electron micrographs of the joints and intensities of characteristic X-rays. (a) Al–Si/steel; (b) Al–Si/Al_2O_3.

the steel–steel joint at 3.0 mm interlayer thickness is almost the same as that of the alumina–steel joint despite the fact that the thermal expansion mismatch is lower in the alumina–steel joint. The strength of the alumina–alumina joint is also shown in Fig. 5 for comparison. The precise reason for this is not clear at present. However, as shown in the previous report [8], the influence of thermal expansion of aluminium used for interlayer cannot be ignored when the interlayer becomes thick. The thermal expansion mismatch between aluminium and steel pipe is considered to be one of the reasons for yielding the above result. More detailed studies will be carried out in the future. From these results it can be concluded that the strength of the alumina–steel joint is controlled by the strength of the interface between interlayer and steel pipe under the condition where the interlayer thickness is more than 2.0 mm.

3.2. Microstructure of the interface

Figure 6 shows scanning electron micrographs of the interface and intensities of characteristic X-ray of aluminium, iron and silicon analysed along the white line. A clear change of the characteristic X-ray intensity of aluminium and silicon cannot be seen at the alumina and the aluminium interlayer interface. Unlike the interface of alumina–interlayer, the reaction layer consisting of aluminium and iron is formed at the steel–interlayer interface. This reaction layer is examined by X-ray microdiffraction (a spot size of 30 µm diameter). The result is shown in Fig. 7. This shows that the reaction layer is an intermetallic compound consisting mostly of Fe_2Al_5. It is easily understood that the strength of the joint will be affected by this intermetallic compound as described in the previous report [8]. Accordingly the effect of the intermetallic compound layer thickness on the strength of the joint is evaluated. The thickness of the intermetallic compound layer is changed by changing the joining time from 0.9 to 7.2 ksec. Figure 8 shows the thickness change of the intermetallic compound of steel–steel joint when the interlayer of 0.16 mm in thickness is used. The thickness of the intermetallic compound layer increases with increasing joining time. Figure 9 shows the relationship between the thickness of the intermetallic compound layer and the strength of the steel–steel joint with 0.16 mm thick interlayer. The strength of the joint decreases in proportion to the thickness of the intermetallic compound. It may be concluded that the intermetallic compound plays an important role in determining the strength of the joint.

3.3. Residual stress

Residual stress is calculated by the finite-element

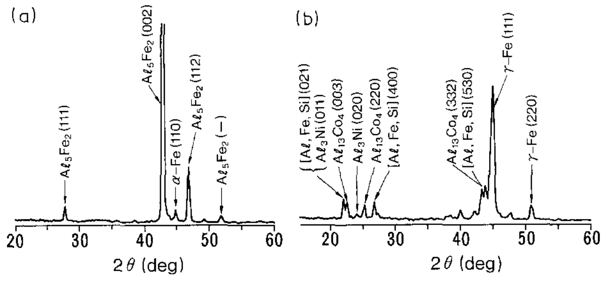

Figure 7 X-ray diffraction patterns of the interface (Cu$K\alpha$, 40 kV, 200 mA). (a) S35C/Al_2O_3; (b) Kovar/Al_2O_3.

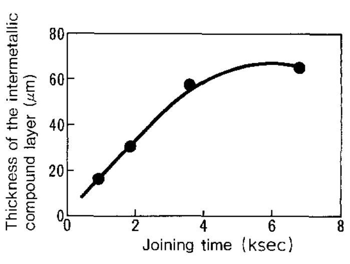

Figure 8 Relationship between jointing time and thickness of the intermetallic compound layer.

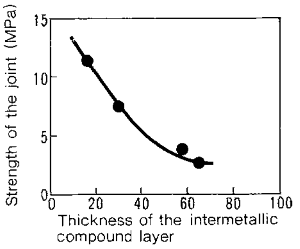

Figure 9 Effect of thickness of the intermetallic compound layer on the strength of the joint.

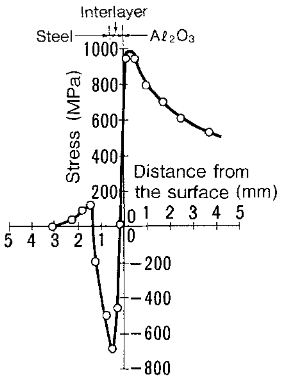

Figure 10 Residual stress distribution by the elastic calculation.

method with a fully elastic model before measuring true stress of the joint. Specimen shown in Fig. 1 and several properties of materials shown if Table I are used for calculation. Figure 10 shows the stress distribution in the axial direction along which the joint interface peels off when the joint is cooled from 873 K to room temperature. The maximum tensile stress, about 1000 MPa, appears in the alumina near the interface. It decreases abruptly with the distance from the interface. To find the stress values accurately the plastic deformation of the specimens must be included but here only the elastic calculation was carried out, because the physical properties of the intermetallic compound layer are unknown. The stress values obtained is far above the true stress, so the stress values themselves are not referred but only the tendency is discussed. Contrary to the alumina, the compressive stress appears in the interlayer and the steel. Considering the fact that the maximum tensile appears in the alumina, the fracture of the joint must be initiated in the alumina. However, most joints are fractured in the interface between the interlayer and the steel. It is considered that the strength of the interface between the interlayer and the steel is lower than alumina itself.

Secondly the true stress of the joint was measured by Sachs method. The results are shown in Fig. 11. Almost the same stress distribution as calculation is recognized although the value of stress is extremely low compared to that by elastic calculation. The tensile stress is recognized in the alumina regardless of interlayer thickness. It is, furthermore, shown that the maximum tensile stress is decreased from 90 MPa to 50 MPa by increasing interlayer thickness and that the tensile stress in the steel pipe with the interlayer of 0.8 mm thickness is changed to compressive stress. From this result, the effect of interlayer thickness on the stress relief of the joint becomes clear.

The strength of the joint increases and the fracture point is transferred from alumina to interface as the tensile stress becomes low. It is, therefore, concluded that the increase of the interlayer thickness decreases the residual stress after joining and increases the stength of the joint, unless the thickness of the intermetallic compound between the aluminium interlayer and steel is changed. But if the thickness of the compound layer changes, more detail study may be needed.

TABLE I Properties of materials

Material	Thermal expansion coefficient (10^{-6} K^{-1})	Young's modulus (GPa)	Poisson's ratio
Al_2O_3	7.1	370	0.23
Al	26.5	72	0.44
Steel	13	210	0.31

4. Conclusion

The effect of residual stress and intermetallic compound on the strength of the alumina–steel joints with Al–Si interlayer was studied. The results are summarized as follows.

1. Joints with both high hermetic seal and strength can be obtained with the use of Al–Si interlayer of more than 2 mm in thickness.
2. The strength of the joints increases with the increase of interlayer thickness and the maximum tensile strength, about 23 MPa, is obtained.
3. The strength of the joints decreases with the increase of intermetallic compound thickness formed between the interlayer and the steel.
4. Measurement of residual stress by Sachs method shows that the residual stress of the joint is extremely low compared with that by the elastic calculation.
5. The residual stress decreases by increasing interlayer thickness.
6. From these results, it becomes clear that the strength of the joint was strongly influenced by the formation of intermetallic compound as well as residual stress.

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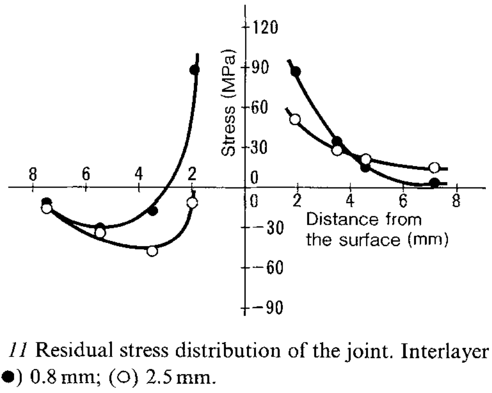

Figure 11 Residual stress distribution of the joint. Interlayer thickness: (●) 0.8 mm; (○) 2.5 mm.

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