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EVALUATION OF BOND STRENGTH OF NI-P-SIC ELECTRONIC PLATING BY LASER SPALLATION TECHNIQUE

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Abstract
We utilized a laser spallation technique to evaluate the bond strength of a Ni-P-SiC plating on an aluminium alloy plate. In this technique, strong tensile stress of longitudinal waves was produced by laser ablation of black ink painted on the sample and was utilized for exfoliating the plating layer. Critical tensile stress (bond strength) causing the delamination was determined from out-of-displacement of the sample surface induced by the waves measured by a laser interferometer. We also performed cross-section indentation testing with a finite element analysis (FEM) for verifying the bond strength estimated by the laser spallation technique. Although the estimated bond strength by the laser spallation method was distributed depending on measurement area as well as indentation testing, the lowest strength estimated by the two methods agreed fairly well.

Keywords: Laser spallation, electronic plating, adhesion force, indentation testing, FEM analysis

1. Introduction

Although it is known that estimation of a bonding state at the interface between a substrate and a surface modified layer is essential for controlling quality of coated products, there is no available method to characterize the bond quality non-destructively. Gupta *et al*. proposed the laser spallation technique for measuring the bond strength in non-contact manner. In this technique, a delamination was caused by strong tensile stress waves generated by a pulsed laser [1-4]. The bond strength can be estimated from out-of-displacement at the sample surface induced by the stress waves, when the delamination occurred. They produced the tensile stress waves by utilizing the conversion of the compressive waves at the coating surface of the sample opposite to a laser irradiation point. Ikeda *et al* also estimated the bond strength of a diamond layer on a SiC plate using the laser spallation method modified by them [5, 6]. The modified method allowed transmitting a strong tensile wave into the interface directly and simplified an estimation procedure of the bond strength.
In this study, we studied the validity of the bond strength estimated by the laser spallation method by comparing the strength by cross-section indentation testing in conjunction with a finite element method.

2. Laser spallation method

2.1 Experimental setup for laser spallation method

Figure 1 shows the experimental setup for the laser spallation method which was developed by Ikeda [5, 6]. High-energy Q-switched YAG laser beam (wavelength: 1.06 μm) of 3.5 mm diameter was irradiated on the sample surface opposite to the surface modified layer. Strong tensile stress waves were produced by a laser ablation of an energy absorbing layer on the surface. We circulated black ink by a roller pump as the absorbing layer instead of the silicon grease used by Ikeda because the silicon grease was completely vaporized or ablated by one shot of laser beam. Continuous supplement of the absorbing layer makes the measurement of the bond strength at exactly the same position and quick measurement possible. Thickness of the ink was controlled to 500 μm by a metallic thickness gauge. Additionally, the absorbing layer was confined rigidly by a thick acryl plate for enhancing generation efficiency of the tensile stress waves. Stress induced by the wave generated by pulse laser can be expressed, according to one-dimensional wave equation, by

$$\boldsymbol{\sigma = \frac{1}{2}\rho V_l \frac{\partial u}{\partial t}} \quad (1)$$

where ρ and V_l are the density and the velocity of the longitudinal wave of the medium. A heterodyne-type laser interferometer was used to measure the out-of-plane displacement, $\boldsymbol{u}$ at the just epicentre of the laser irradiation point. The coefficient of 1/2 is a factor for estimating stress inside the medium from the out-of-plane displacement at the surface. The interferometer was trigged by a leaked YAG laser beam.

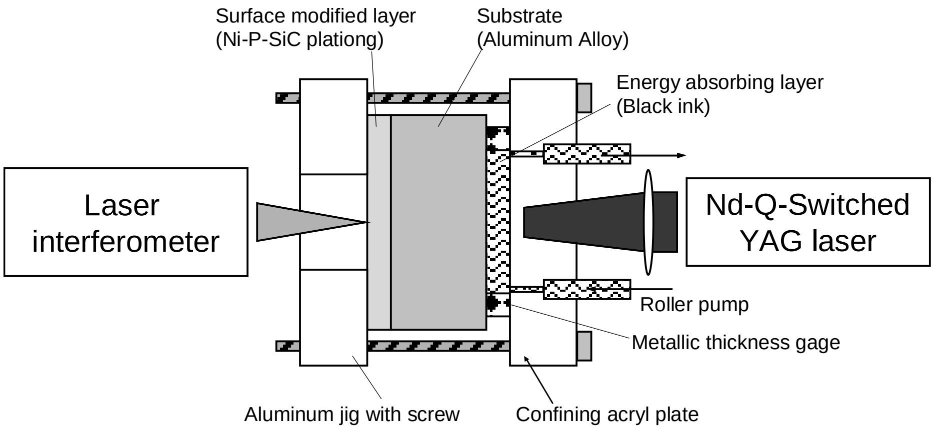

Figure 1 Experimental setup for laser spallation method

Figure 2 compares the out-of-plane displacements detected at the epicentre of the laser irradiation point as a function of laser energy from 30 mJ to 50 mJ for an Al alloy plate with thickness of 5 mm. Large positive pulse on longitudinal waves followed by a negative pulse was observed and their amplitude increased with laser energy. The tensile stress causing delamination of the surface layer was produced by the wave having a positive slope. Figure 3 shows the relationship between tensile stress calculated by equation (1) and laser energy. The tensile stress almost proportionally increased with increasing laser energy to 53 mJ and reached approximately 110 MPa. At laser energy more than 53 mJ, the tensile stress slightly decreased and did not exceed 110 MPa which is a stress corresponds to elastic limit of the Al alloy used. We observed a slight deformation on the sample surface at the laser irradiation point. These facts implied that a part of the energy of the stress waves produced by the laser ablation was used for plastic deformation of the sample. We used the relation shown in Fig.3 for estimating a bond strength of a plating layer discussed in the next section.

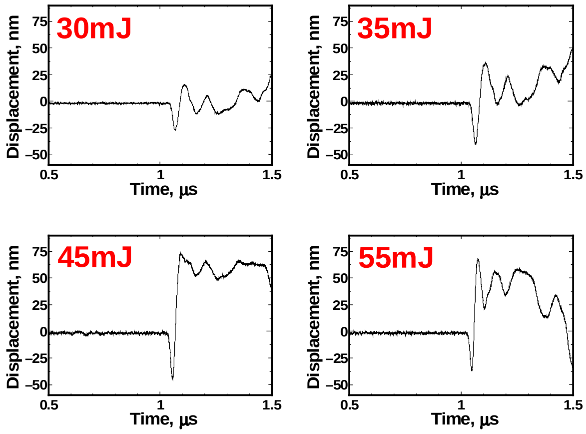

Figure 2 Out-of-plane displacements as a function of laser energy

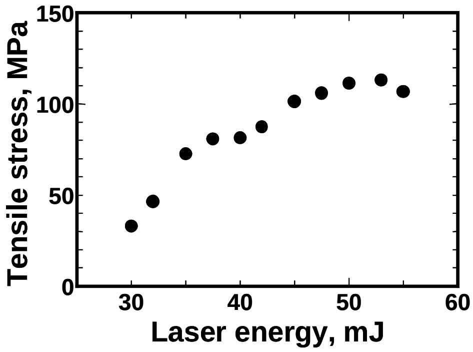

Figure 3 Relation between laser energy and stress calculated by equation (1)

2.2 Bond strength of Ni-P-SiC plating

We prepared a Ni-P-SiC electronic plating sample on the same Al alloy substrate as described in the previous section. Dimension of the sample was 50 mm^W x 30 mm^L x 5 mm^t. Ni-P-SiC plating was performed after electro polishing the substrate and was anodized. Thickness of the plating was 60 µm. The spallation testing for the sample was carried out using the experimental setup shown in Fig.1. The diameter of the Nd:YAG laser spot size was 3.5 mm. Laser energy was increased from 35 mJ to 55 mJ by 2.5 mJ until the delamination occurred. Corresponding tensile stress changed from 68 MPa to 110 MPa as shown in Fig.3.

Fig.4 shows the bond strength of the sample estimated by the laser spallation technique. The bond strength (squares in Fig.4) was estimated for five points by translating the sample by 5.0 mm step. This figure also shows the bond strength (closed circles) estimated by the indentation testing discussed in the next section. Horizontal axis means the distance from the sample edge. The estimated bond strength varied from 68 MPa to more than 110 MPa depending on the measurement points. The bond strength was determined as the stress induced by the wave generated by laser spallation technique when the delamination occurred. The delamination was detected by utilizing nonlinear interaction of the interface with a delamination and elastic waves [7].

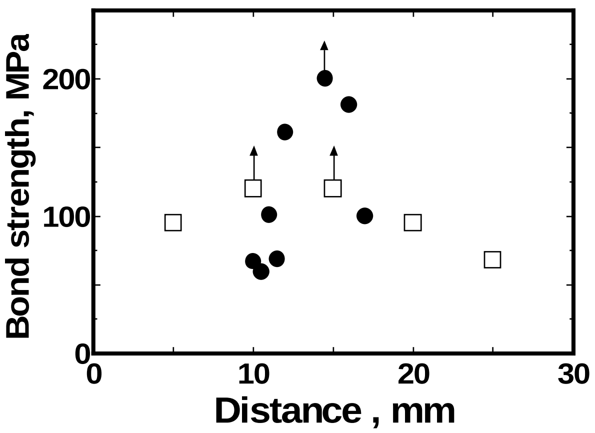

Figure 4 Bond strength estimated by laser spallation and indentation method.

Figure 5 shows cross-sectional images after laser spallation testing at laser energy of 35 mJ (a) and 37.5 mJ (b). No delamination was observed in Fig.5(a) In Fig.5(b), we clearly observed small delamination. These observations supported the results of the delamination detection utilizing nonlinear effect at the interface. Therefore, we could determine the bond strength as critical stress causing delamination induced by laser spallation technique in non-contact manner.

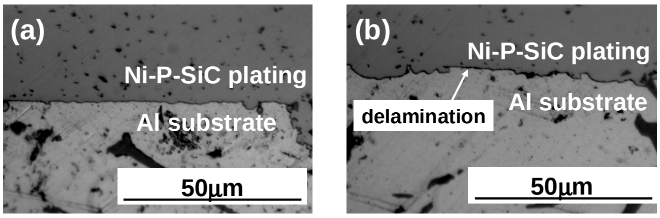

Figure 5 Cross-sectional images after laser spallation test at laser energy of (a) 35 mJ and (b) 37.5 mJ

3. Indentation testing in conjunction with FEM analysis

We also evaluated the bond strength of the same sample submitted to the laser spallation test by an indentation test and FEM analysis. Experimental setup for the indentation test is shown in Fig.6. We performed indentation test by an electromagnetic type servo-testing machine equipped with a Vickers indenter under the control of indentation force ***F***. Indentation force rate and maximum force were set to be 0.04 N/s and 20 N, respectively. Indentation depth (***h***) was measured by two eddy current displacement sensors at the both side of the indenter. Indentation testing was preformed on cross-section of the sample 5 mm away from laser spallation testing area. Indenter was impressed near the interface to introduce Mode-I fracture along the interface. We also monitored acoustic emission (AE) signals produced by the Mode-I fracture during indentation testing. We used two small PZT type AE sensors (Diameter: 3.0 mm, centre frequency: 450 to 500 kHz) attached on the both side of the sample. All output signals were fed to and was stored in the computer.

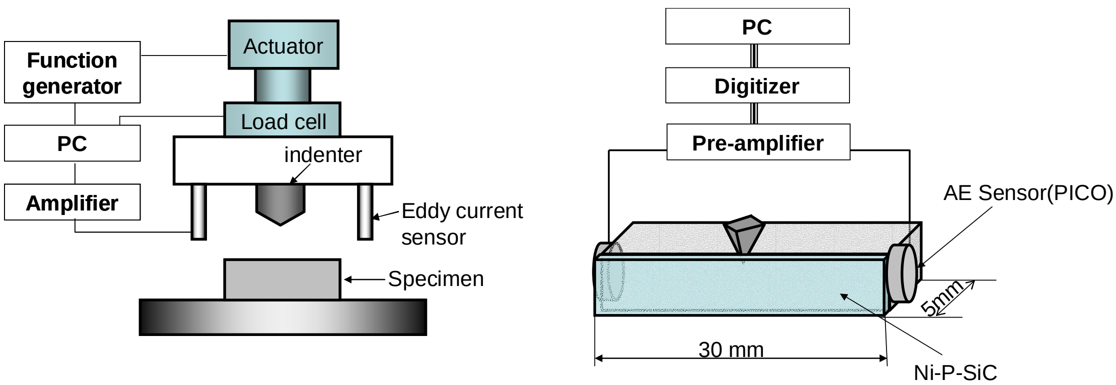

Figure 6 Experimental setup for indentation testing

Figure 7 shows measured typical ***F-h*** curve shown by thick line and AE generation timing during indentation testing. Open triangles near the curve indicated AE generation timing. We also show FEM analysis results (calculated ***F-h*** curve (○)

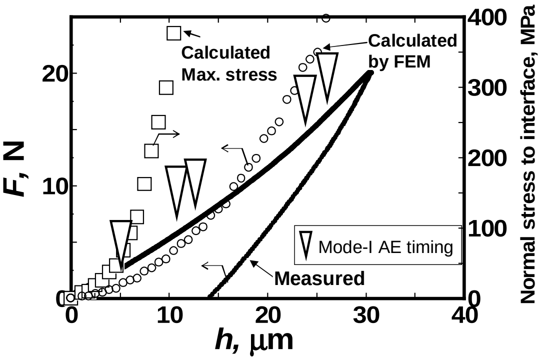

Figure 7 Measured and calculated ***F-h*** curves, AE generation timing and the calculated resulting maximum stress acting on the interface

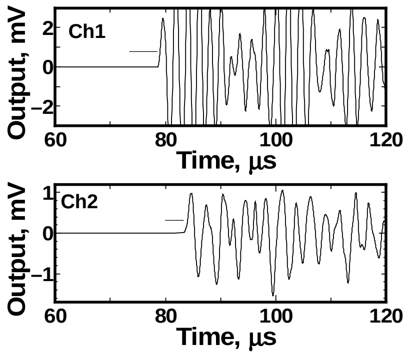

Figure 8 Typical AE waveform detected during the indentation testing

and the stress (☐) normal to the interface acting on the interface) in Fig.7. Fig.8 shows the typical AE waveforms detected during loading. AE propagated as Lamb waves. It is noted that polarities of fundamental symmetrical mode of Lamb waves are all positive as indicated by arrows, indicating Mode-I opening fracture type [8]. Fig.9(a) shows the optical image after indentation testing. Fig.9(b) shows the expanded image around contact region of Fig.9(a). Delamination was observed along the interface as indicated by AE analysis. Using AE technique, we determined a critical indentation load when the Mode-I fracture initiated during indentation testing.

We next evaluated the bond strength by FEM analysis of the indentation testing. Figure 10 shows a top view of three dimensional FEM model for the indentation testing. 16640 elements were used. Young's modulus and yielding stress of the substrate were measured as 68 GPa and 120 MPa by tensile testing. Young's modulus and yielding stress of the plating layer were also evaluated as 150 GPa and 1.85 GPa by dual indentation test [9]. These mechanical properties were used for FEM analysis. Position of the indenter on FEM analysis was determined so as to correspond to that for indentation testing.

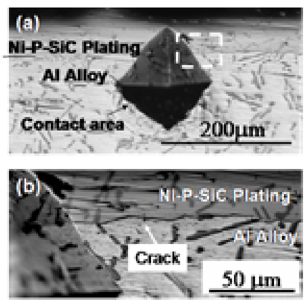

Figure 9 Micrograph of contact region for Ni-P-SiC / Al alloy using a Vickers indenter

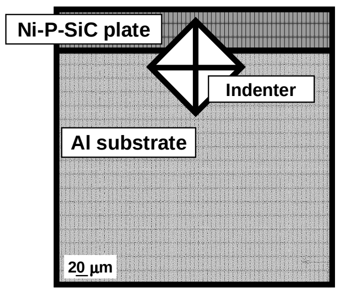

Fig.10 Top view of three dimensional FEM model for Ni-P-SiC / Al alloy

Calculated ***F-h*** curve (○) and change of resulting maximum stress normal to the interface acting on the interface (☐) during loading process were shown in Fig. 7. Calculated curve agreed fairly well with an experimental one in lower loading regime. We determined the bond strength as the maximum stress at the critical indentation load where first AE signal caused by Mode-I fracture was observed. Estimated bond strength by indentation testing were shown as closed circles in Fig.4 and ranged from 70 MPa to 1100 MPa. The lowest strength estimated by indentation testing agreed with that by laser spallation technique. However, as the laser spallation method could not produce the tensile stress to the interface beyond the elastic limit of the substrate, we could not compare the highest value by between the two methods.

4. Conclusions

We evaluated of the bond strength of Ni-P-SiC plating on an aluminium alloy substrate by both the laser spallation technique and indentation testing in conjunction with FEM analysis. The results were summarized below

1) Utilizing laser spallation technique, we evaluated the bond strength of Ni-P-SiC deposited on Al alloy. The estimated bond strength of Ni-P-SiC was changed from 68 MPa to more than 110MPa depending on the measurement points.

2) We also estimated the bond strength utilizing indentation test in conjunction with finite element method for verifying the validity of the bond strength estimated by the laser spallation technique. Estimated strength by the indentation method also varied in the range of 70 MPa to 1100 MPa. However, the lowest strength estimated by both the indentation testing and the laser spallation technique were in good agreement.

Acknowledgements
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