

Activation Spot Joining between Aluminum Alloy and High-strength Steel Sheets using Friction Surfacing

Goro Watanabe, Hisaaki Takao, Toshiaki Yasui, Masahiro Fukumoto

Abstract— The bonding between ultra-high-strength steel sheet and Al alloys was successfully improved by using friction surfacing and activation spot joining. This new procedure consists of pressing a rotating consumable Al tool into the side of the Al sheet that will be bonded to the steel sheet. The tool is held in place for a specified time until an overlay is formed, and then it is removed to form the spot joint for the Al/steel bond. In this technique, a hole is first drilled from the Al side. The hole increases the plastic flowability and readily exposes a fresh Al surface. SPC980 ultra-high-strength steel and A6061 Al alloy, materials of high interest for light structural applications, were bonded in this study. When high tensile steel with a thick oxide surface film was polished before the bonding process, the tensile shear strength (TSS) and cross tensile strength (CTS) of the joint was approximately twice that of a joint of unpolished steel. The oxide layer remaining in the bond interface was greatly reduced by the polishing treatment; it was found that the thin (several tens of nanometers) Fe-Al compound layer formed at the same time was a factor in the improvement of joint strength. It was also observed that the reducing action of Mg at the bond interface was greatly accelerated and Mg oxides took on a particle shape before diffusing. These events appear to be key factors in the disappearance of the interface oxides.

Index Terms— Dissimilar metal, Friction surfacing, FSSW, High-strength steel, Surface polishing

I. INTRODUCTION

The automotive industry has been forced into continual efforts to lighten automobile bodies to minimize CO₂ emissions and resource consumption [1]–[3]. This has led to the increasing use of aluminum alloys and high-tensile-strength steel sheet, a material with high specific strength, in the manufacture of automobile bodies. This necessitates joining dissimilar materials. However, conventional joining methods such as resistance spot welding cause brittle intermetallic compounds (IMCs) to form at the bond interface [4]–[6]. The IMCs undermine bond integrity between the steel sheet and the Al alloy. Self-piercing rivets (SPR) and other mechanical joining methods can also be employed, but doing so leads to higher component costs [7], as well as the difficulty of inserting rivets into the

Goro Watanabe, Material & Processing Dept. 1, Toyota Central R&D Labs., Inc. and D.Eng student in Department of Mechanical Engineering, Toyohashi University of Technology, Japan.

Hisaaki Takao, Material & Processing Dept. 1, Toyota Central R&D Labs., Inc., Japan.

Toshiaki Yasui, Department of Mechanical Engineering, Toyohashi University of Technology, Japan.

Masahiro Fukumoto, Department of Mechanical Engineering, Toyohashi University of Technology, Japan.

increasingly popular ultra-high-strength steel, which boasts strengths of 980 MPa or more [8].

The solid-state process of friction stir spot welding (FSSW) has attracted attention in recent years and its applicability to Al/Fe bonding has been investigated. There are concerns about the joint strength obtained by these technologies, however; the strength is often unsatisfactory due to the tool-shaped concavities formed in the sheet and the consequent thinning of the material beneath. The authors have proposed using activation spot joining (ASJ), which uses a consumable Al tool that establishes the bond while compensating for deficits in material thickness [9]. We examined the static strength, interface morphology and other parameters of bonds between Al and mild steel sheet and demonstrated that this procedure is effective. However, issues still remain concerning the low strength levels in bonds with promising ultra-high-strength steel. Below, we report the results of our investigation of the causes of these issues and how to approach them.

II. EXPERIMENTAL WORK

A. Materials and Joining Procedure

The Vertical Machining Center was used for the joining to precisely control the rotational speed and tool plunge depth. The chemical compositions of the workpiece materials are listed in Table I. As shown schematically in Fig. 1, ASJ was implemented by using an Al alloy rod (A2017, 10 mm diameter) to maintain the joint thickness. The rod was pressed and rotated into an Al alloy sheet to simultaneously

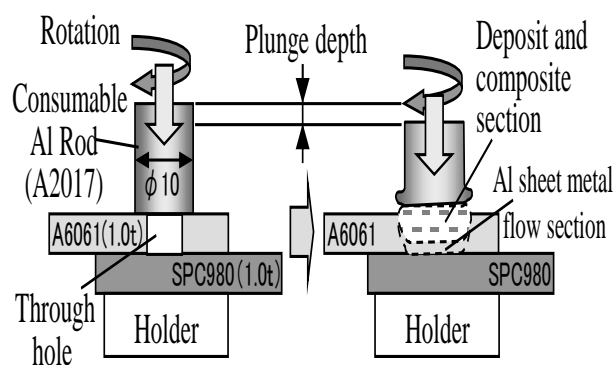


Fig. 1 Schematic illustration of activation spot joining using friction surfacing.

Table I. Chemical composition of workpiece materials (mass%).

%Wt	SPC980	A6061	A2017
Silicon (Si)	0.97	0.59	0.50
Iron (Fe)	balance	0.38	<0.70
Copper (Cu)	-	0.26	4.00
Manganese (Mn)	2.16	0.03	0.70
Magnesium (Mg)	-	0.96	0.60
Chromium (Cr)	-	0.25	<0.10
Zink(Zn)	-	0.02	<0.25
Titanium (Ti)	-	0.04	<0.20
Carbon (C)	0.13	-	-
Phosphorus (P)	0.011	-	-
Sulfur (S)	0.004	-	-
Aluminum (Al)	-	balance	balance

Table II. Spot joining conditions.

Tool rotation	N (rpm)	1500
Tool plunge speed	v (mm/s)	0.5
Tool plunge depth	PD (mm)	1.2
Hold time of tool	t (s)	1, 2, 3, 5, 7, 10
Through hole diameter	dia. (mm)	7

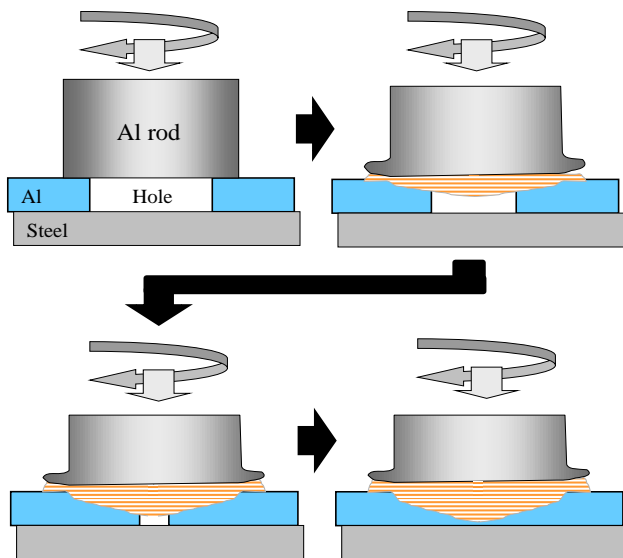


Fig. 2 Inference of plastic flow behavior for activation spot joining.

produce friction and an Al deposit. The deposit was removed after a given holding time to complete the spot joint between Al alloy sheet (A6061-T6, t1.0) and ultra-high-strength steel sheet (SPC980, t1.0). The values of rotational speed N , plunge speed v , and plunge depth PD, which were optimized for the operating conditions, are given in Table II. The hold time t was varied in the range 1–10 s in this experiment.

As shown in another study [9], a through hole (7 mm diameter) was drilled in Al alloy. As the Al alloy rod was lowered into the hole, the Al sheet metal around the hole flowed into the center, closed the hole, and thus formed a joined layer with the surface of the steel sheet. When this was

done, the Al alloy rod did not itself come into contact with the steel sheet; it was the Al alloy sheet, which had been expanded and thinned, that contacted the steel sheet. It was observed that the naturally oxide film of the Al was fragmented and exposed a fresh Al surface, and the activated Al displayed an increased bonding strength with the steel sheet. The inferred plastic flow behavior is presented in Fig. 2, which shows the time-dependent change when the rod was pushed in.

The high tensile steel surface was also polished in this experiment to vary the surface conditions. Emery paper (#800) was applied by hand to the material surface for 100 alternating passes in each direction. The surfaces of all polished and unpolished specimens were washed with acetone before the bonding operation.

B. Methods of Analysis and Tensile Testing

The resulting joint strength was assessed in terms of the tensile shear strength (TSS) and cross tensile strength (CTS) according to JIS Z3136 and JIS Z3137. Fig. 3 shows the shape of the test specimens. The tests were performed on a 10-ton universal testing machine.

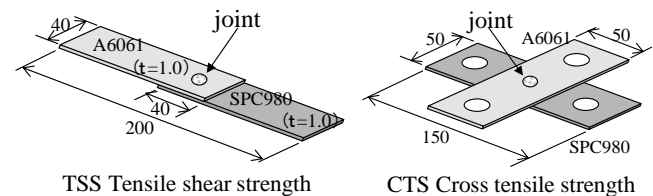


Fig. 3 Tensile test specimen.

To evaluate the bonding mechanisms, the thickness of the oxide film of the high tensile steel was examined by X-ray photoelectron spectroscopy (XPS), the bond interface was observed by scanning electron microscopy (SEM) and annular dark-field scanning transmission electron microscopy (ADF-STEM). The element assay was carried out by energy-dispersive X-ray spectroscopy (EDS).

Temperatures during bonding were measured with a thermocouple on the rear surface of the steel sheet and a radiation thermometer oriented at the edge of the tool. Both provided temperatures near the bonding location; the temperatures reached about 400°C and this remained approximately constant throughout the hold time.

III. RESULTS AND DISCUSSIONS

A. Tensile Test

Fig. 4 provides the results following a bonding test at the hold time of 2 s (3 specimens).

The mean CTS and TSS values for joints incorporating unpolished high tensile steel were 0.25 kN and 2.68 kN, respectively. In comparison, the values for polished material were 0.66 kN and 6.23 kN, which were twice the strength of the unpolished specimens (failures in both conditions were interfacial fractures). The remaining Al areas adhering to the steel sheets were evaluated; the areas were larger in the polished steel specimens. The stress levels in TSS were about

69 MPa in the unpolished specimens and 107 MPa, or about 50% higher, in the polished specimens (Fig. 5).

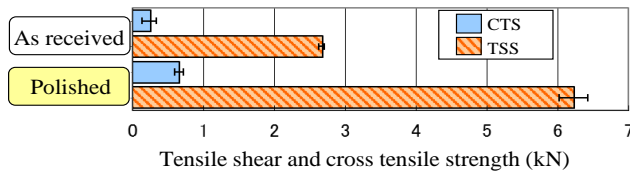
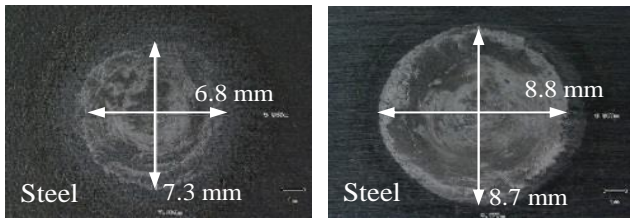


Fig. 4 Results of tensile strength test.



(a) As received (69 MPa) (b) Polished (107 MPa)

Fig. 5 Fractured surfaces of steels after TSS measurements.

B. Observations of Bond Interface

Fig. 6 presents SEM images of the bond interface polished by Ar ion. The unpolished specimen (a) showed an uneven steel surface with submicron-scale bumps and hollows; in contrast, the polished specimen (b) was quite flat and smooth. Nevertheless, even in the unpolished specimen, the Al material filled the intervening gap with almost no cavities, and no remarkable voids were observed. Thus, both specimens had identical high levels of the actual bond area ratio. Hence, the lower joint strength in the unpolished specimens as compared with the polished specimens appears to not be due to the surface morphology.

C. Evaluation of Oxide Surface Film

The thickness of the oxide surface films of the specimens was examined for variations as a possible influence on joint strength. The polished specimens were observed after

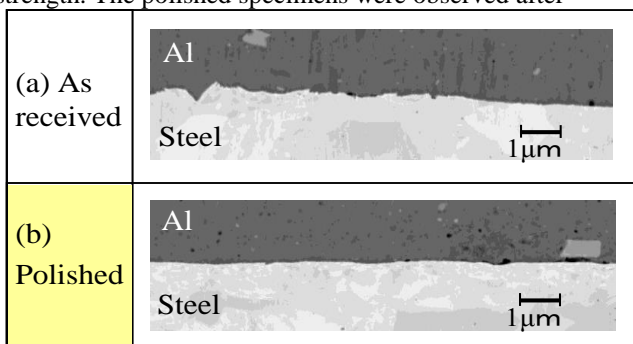
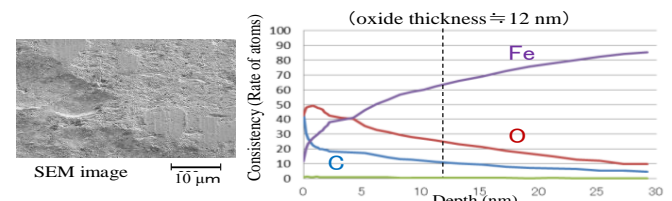


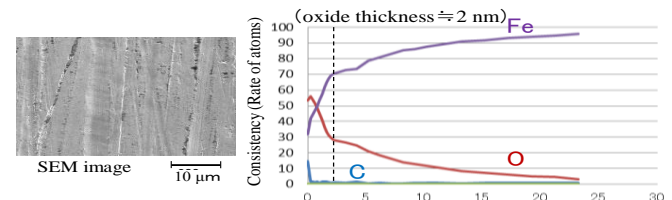
Fig. 6 Comparison of SEM images of joint interface with (a) and without (b) polishing of ultra-high-strength steel. (cross-section polishing)

exposure of their polished surfaces to the atmosphere for about half a day. The steel plate surface was gradually removed by Ar sputtering while the element assay was carried out by XPS to obtain the profile versus depth. Fig. 7 shows the results for the unpolished (a) and the polished (b) specimens. The depth at which the oxygen content reached half the value of that at the surface was used to approximate the oxide film thickness. This depth was found to be approximately 12 nm in the unpolished specimens (a) and 2

nm in the polished specimens (b). A large number of alloying elements including Si and Mn strengthened the steel sheet. Because these elements are quite easily oxidized [10], it is no surprise that the high tensile steel surface had a thick oxide film.



(a) As received steel surface (XPS depth profile analysis)



(b) Polished steel surface (XPS depth profile analysis)

Fig. 7 Comparison of surface oxide thickness without (a) and with (b) polishing of ultra-high-strength steel.

D. STEM Analysis of Bond Interface

Fig. 8 presents the ADF-STEM images and the element assay results for the bond interface in the unpolished (a) and

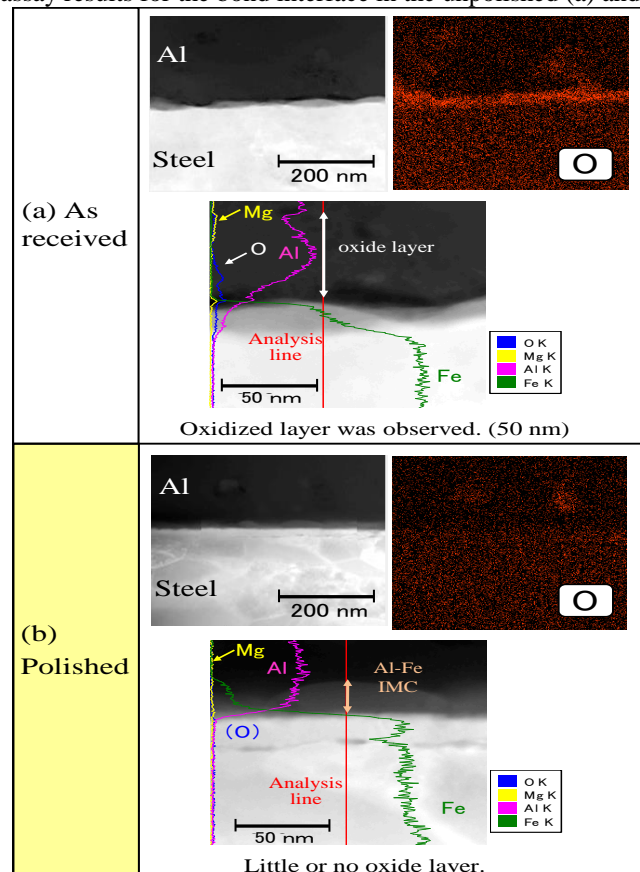


Fig. 8 Comparison of STEM images, oxygen distribution maps and line analysis of joint interface without (a) and with (b) polishing of ultra-high-strength steel.

polished (b) specimens of high tensile steel. The steel portions, with the higher atomic numbers, are the brighter portions of the STEM images. The bond interface in (a) contains gray layers several tens of nanometers across, but this indicated the uneven surface morphology of the steel and

was not the reactive layer. The element distribution clearly shows the presence of an oxide layer at the surface. From the line distribution, the approximately 50 nm thick oxide layer was composed of Al, Mg, and O. In contrast, the oxide film at the interface in the polished specimen (b), which had a small oxide film on the steel surface, was far reduced in thickness from that of (a). A dark-gray continuous thin reactive layer was also observed on the interface. From the line distribution, we see that the approximately 20 nm thick reactive layer is mainly composed of Al and Fe.

We attempted to obtain a diffraction pattern from these reactive layers for the purpose of identifying the materials, but the width of the portion under examination was too low to provide a pattern. Nevertheless, the element ratios revealed by a point analysis corresponded to $FeAl_3 - FeAl_6$, and so suggested that Fe had diffused into the Al matrix to form an Al-rich IMC layer. Another study [11] stated that once an oxide layer has formed in the Fe-Al weld interface, the layer acts as a barrier and suppresses reaction diffusion. This may well be the reason that no Fe-Al reactive layer formed in (a) and reaction diffusion occurred in (b).

It has been reported that Al-rich IMC layers, of which typical examples are $FeAl_3$ and $FeAl_5$, are brittle and have poor mechanical properties [12]; on the other hand, the joint strength is higher when the IMC layer is thin, namely, approximately 1 μm [13]. Under the procedure used by the authors for polished high tensile steel, the welding was done at a low temperature for a short time (about 400°C for about 2 s), and the IMC layer was quite thin. With thicknesses of several tens of nanometers, it was more than a factor of 10 thinner than the previously accepted ideal value (1 μm). This result suggested that it may be possible to further improve the joint mechanical characteristics.

Fig. 9 shows findings from STEM analyses of the same material as in Fig. 8, but at low magnification. The alloying elements were Mg and Si. Notable characteristics of this alloy include the following. Mg acted as an oxygen getter and clustered at the interface, and particle Mg oxides formed and then diffused to the upper part of the interface. No Mg or Si compounds were found here in any quantity. The removal of oxides from the interface is an extremely important

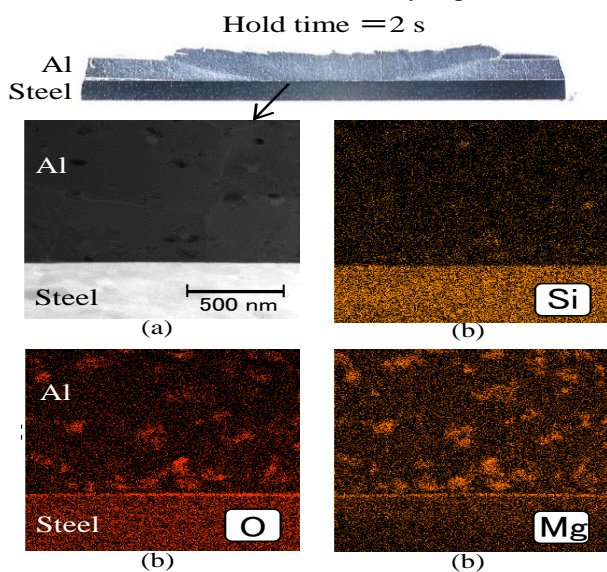


Fig. 9 ADF-STEM (a) and EDS element (b) mapping of joint interface on lower magnification.

process in activation spot joining, and thus using Mg-Al alloy sheet drastically accelerates the reducing action of Mg.

E. Influence on Hold Time

Fig. 10 presents variations in TSS and the typical resulting weld cross sections as the hold time was varied in polished high tensile steel. High scatter was seen in the overlay thickness and, accordingly, in TSS, at the hold time of 1 s. TSS tended to reach its potential around 6 kN at hold times of at least 2 s. The mode of fracture was interfacial or combined-mode interfacial fracture, which is associated with fracture of the base material. It was not necessary to increase the overlay height, and so the desired hold time appeared to be around 2–3 s.

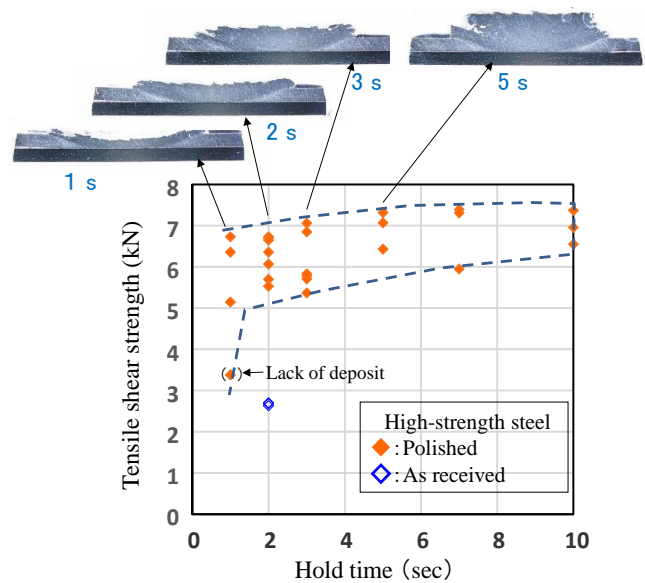


Fig. 10 Effect of the hold time on the TSS and cross-section shape of the joint.

IV. CONCLUSION

Friction surfacing and activation spot joining of ultra-high-strength steel and aluminum alloys were investigated for the purpose of improving the bonding, and the following results were obtained.

- (1) Joints with superior mechanical properties were successfully formed when bonding had been performed after polishing high tensile steel with a thick oxide surface layer. The joint strengths (TSS, CTS) were about double the values of the joints made with unpolished steel.
- (2) The oxide layer remaining in the bond interface was greatly diminished when specimens had been polished. At the same time, the barrier to the diffusion of elements disappeared, and it was found that the formation of a thin Fe-Al compound layer (several tens of nanometers in thickness) was the cause for the improved joint strength.
- (3) When Mg-Al alloy sheet is employed, the reducing action of Mg at the bond interface was observed to be greatly accelerated; Mg oxides took on a particle shape, and these oxides then diffused away from the interface. This also appeared to be a key factor in the disappearance of oxides at the interface.

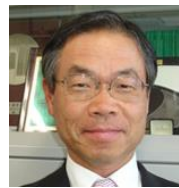
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from Nagoya University in 1993 and D.Eng from Osaka University in 2004. He has 21 years of research experience and he has published total of 19 research papers 8 in international journals and 25 in conferences.



Toshiaki Yasui, is working as Associate Professor in Department of Mechanical Engineering, Toyohashi University of Technology. He has done his M. Eng in 1991 and D. Eng in 1994 from Osaka University. He has 20 years of teaching experience and he has published total of 93 research papers 44 in international journals and 124 in conferences. He is member of an executive board of Japan Friction Joining Association and Japan Thermal Spray Society.



Masahiro Fukumoto, is working as Dean and Professor in Department of Mechanical Engineering, Toyohashi University of Technology. He has done his M. Eng in 1980 and D. Eng in 1984 from Keio University. He has 31 years of teaching experience and he has published total of 365 research papers, 185 in international journals and 180 in conferences. ASM international Fellow, JSME Fellow, JSAE Fellow, JWS Fellow and Former President of Japan Thermal Spray Society.



Goro Watanabe, is working as Senior Researcher in Material & Processing Dept. 1, Toyota Central R&D Labs., Inc. and D.Eng student in Department of Mechanical Engineering, Toyohashi University of Technology. Has done M.Eng from Osaka University in 1983. Has 31 years of research experience and has published research papers 1 in international journals and 3 in conferences.



Hisaaki Takao, is working as Principal Researcher in Material & Processing Dept. 1, Toyota Central R&D Labs., Inc., he has done his M.Eng