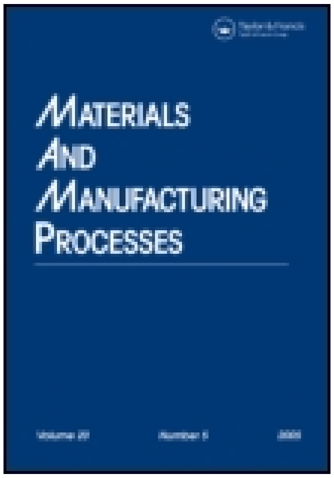

Materials and Manufacturing Processes

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lmmp20

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Accepted author version posted online: 09 Jul 2012.Published online: 26 Nov 2012.

To cite this article: Hongxin Shi , Shuang Qiao , Ranfeng Qiu , Xiaojiao Zhang & Hua Yu (2012) Effect of Welding Time on the Joining Phenomena of Diffusion Welded Joint between Aluminum Alloy and Stainless Steel, Materials and Manufacturing Processes, 27:12, 1366-1369, DOI: 10.1080/10426914.2012.663122

To link to this article: http://dx.doi.org/10.1080/10426914.2012.663122

Materials and Manufacturing Processes, 27: 1366–1369, 2012

ISSN: 1042-6914 print/1532-2475 online
DOI: 10.1080/10426914.2012.663122

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In the present study, direct diffusion welding of aluminum alloy 5A02 and stainless steel SUS304 has been carried out in vacuum in the welding time range of 35–110 minutes. The effect of welding time on the interfacial microstructure and tensile shear strength of the joint were investigated. The joint with tensile shear strength of 101.3 MPa was obtained under the condition of the welding time of 60 minutes. The results reveal that the reaction layer thickness increases with the increasing of welding time and that the reaction layer consists of Al_5Fe_2 and $Al_{13}Fe_4$ formed in the interface. The strength of the joint is related to the reaction layer thickness and the value of the joint strength reached maximum when the reaction layer thickness was approximately 0.8 μm.

Keywords Aluminum alloy; Diffusion welding; Reaction layer; Stainless steel; Strength.

Introduction

The need for joints between dissimilar materials often arises in modern industry, because sound joints between dissimilar materials enable multimaterial design methodologies and low cost fabrication process to be employed [1]. From the view of material supply, aluminum alloys and steels are the most important construction materials. Therefore, the availability of a sound joining technique between aluminum alloy and steel is indispensable.

However, the joining between the two kinds of materials accompanies some difficulties, because of the large difference in physical and thermal properties between aluminum alloy and steel, and the formation of brittle reaction products at the welding interface. Recently, many researchers sought to join aluminum alloy and steel using the several welding methods such as resistance spot welding [2–4], MIG welding-brazing [5], friction welding [6], magnetic pulse welding [7], and friction stir welding [8]. The preceding studies reveal that the joining performance is related to the combination of materials and/or the welding methods employed [2, 5]. Diffusion welding (bonding) is a solid-state joining process capable of joining a wide range of metal and ceramic combinations to produce various components for advanced engineering requirements [9]. The microstructure and mechanical properties of diffusion welded joint would be improved because the solid-state joining method has several advantages over the conventional fusion welding processes [10]. Nevertheless, few studies have been reported on the diffusion welding between aluminum alloy and stainless steel.

Therefore, this study seeks to join aluminum alloy and stainless steel using direct diffusion welding. The effects of welding time on the joining phenomena and mechanical properties of vacuum diffusion welded lap joint between aluminum alloy and stainless steel were investigated. And then, the relationship between the interfacial reaction layer thickness and the tensile shear strength of the joint was further studied. This study contributes to better understanding of the effect of interfacial reaction layer on the mechanical properties of dissimilar materials and provides some foundational information for improving mechanical properties of the joint.

Experimental procedure

In this study, 3.0 mm thick commercially aluminum alloy 5A02 (5A02) sheet and stainless steel SUS304 (SUS304) were used as base materials. Their chemical compositions are listed in Table 1. Figure 1 shows the configuration and dimension of the joint. Figure 2 shows the vacuum diffusion welding cycle adopted in this study. Welding conditions of the direct diffusion welding are given in Table 2, in which the welding times were varied from 35 minutes to 110 minutes with the interval of 25 minutes.

Before welding, the oxides on the surface of aluminum alloy sheet were removed with abrasive paper, and then the surface of aluminum alloy sheet and stainless steel sheet were cleaned with acetone to remove grease and residue.

After welding, the joint was cut from welded zone perpendicular to the welding interface, The specimen obtained was ground and polished. In order to ensure that the joint was not damaged during machining

Received April 15, 2011; Accepted November 13, 2011

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TABLE 1.—Chemical composition of the base alloys (wt%).

5A02	Mg	Fe	Cr	Si	Mn	Cu	Zn	Al
	2.2	0.27	0.19	0.09	0.049	0.027	0.005	Bal.
SUS304	Cr	Ni	Mn	Si	C	P	S	Fe
	18.0	8.0	1.25	0.85	0.06	0.04	0.02	Bal.

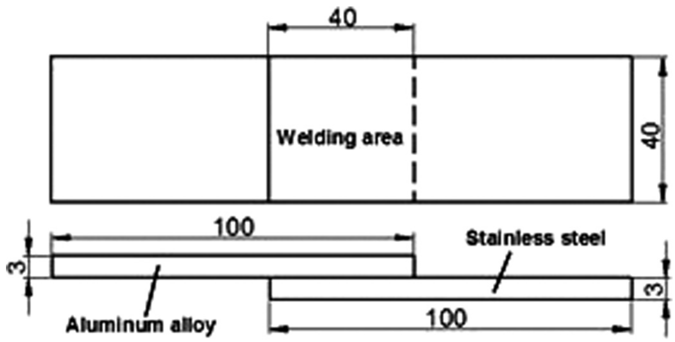

FIGURE 1.—Configuration and dimension of the joint.

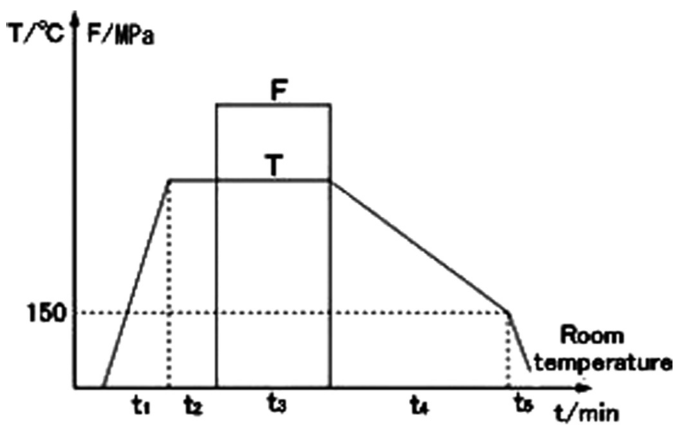

FIGURE 2.—Schematic diagram of vacuum diffusion welding cycle.

operation, the joint was embedded using resin before cutting. The microstructure near the joining interface was observed using a scanning electron microscope (SEM, JSM-560LV) with an energy dispersive X-ray spectroscopy (EDX) analysis. The thickness of reaction layer formed at the joining interface was measured as the average value in $30 \times 30\,\mu m$ SEM image taken every $100\,\mu m$ along the interface. In order to examine the mechanical properties of the joint, the tensile shear test was performed using the material testing machine (AG-1/250 KN) under a crosshead speed of 1.7×10^{-5} m/s at room temperature. The tensile shear strength of joint was calculated by fracture surface area and tensile shear load of the joint. The joint tensile shear load and fracture surface area was determined based on the average value over three measurements per condition.

TABLE 2.—Welding conditions of the direction diffusion welding

t_1 (min.)	t_2 (min.)	t_3 (min.)	T (°C)	F (MPa)
30	5	35	525	10.9
30	5	60	525	10.9
30	5	85	525	10.9
30	5	110	525	10.9

RESULTS AND DISCUSSION

Figure 3 shows SEM images of the interfacial region of the various joints. As shown in Fig. 3(a), almost no reactant was observed at the interface of the joint welded at the welding time of 35 minutes. At the interface of the joint obtained at the welding time of 60 minutes, the intermittent reactants were observed. When welding time was more than 85 minutes, the reactants at welding interface became continuous shape (reaction layer), as shown in Fig. 3(c). The reaction layer with the maximum thickness of approximately $3.3\,\mu m$ was observed in this study, when welding time reached to 110 minutes. It is well known that interfacial reaction layer thickness (X) is a function of interaction time (t) and temperature (T) and that is described by the equations $X = (2\ Kt)^{0.5}$ and $K = K_0 \exp(-Q/RT)$ (here: K is growth constant, K_0 is constant, R is the gas constant, and Q is the activation energy for growth of reaction layer) [11, 12]. Thus, the reaction layer thickness varied with the increasing of welding time as shown in Fig. 3, which is consistent with above-mentioned equation relationship between the interfacial reaction layer thickness and the welding time on the whole.

Figure 4 shows the EDS analysis results near the interface of the joint obtained from the condition of 110 minutes welding time. As shown, the element Al, Fe, Cr, and Ni were detected in the reaction layer, and the content of Cr and Ni was lower. The content of element Al and Fe has a relatively stable section in the reaction layer, which means that some intermetallic compound between Al

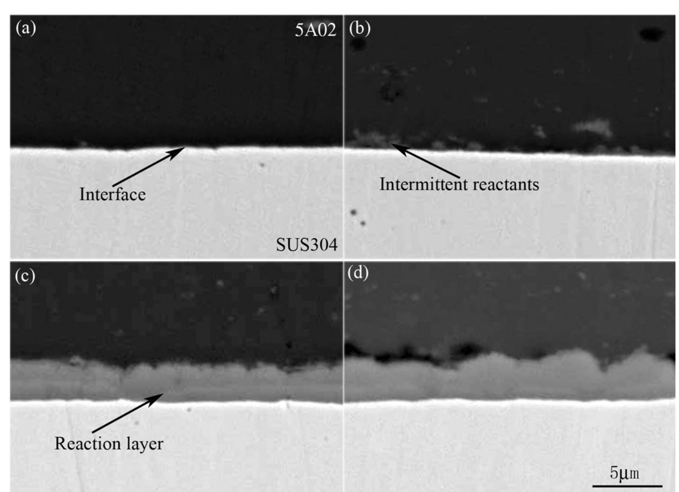

FIGURE 3.—Interface and thereby SEM photographs of the joint obtained at (a) 35 minutes, (b) 60 minutes, (c) 85 minutes, and (d) 110 minutes.

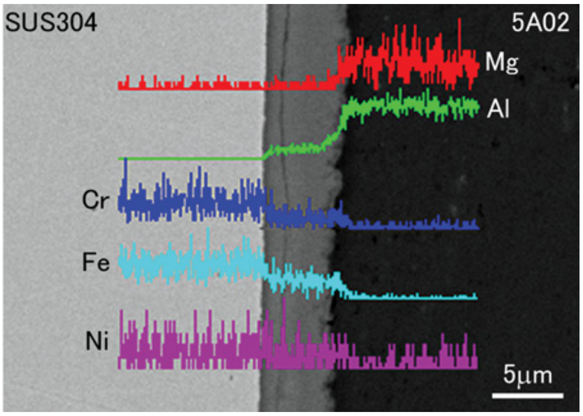

FIGURE 4.—Element line analysis near the joining interface of the joint (color figure available online).

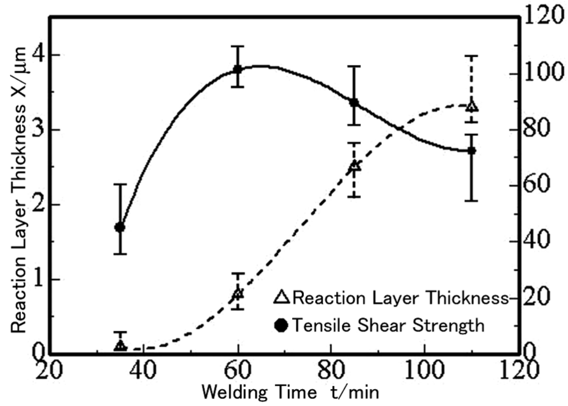

FIGURE 5.—Effects of welding time on the reaction layer thickness and the tensile shear strength of the joint.

and Fe formed in the reaction layer. According to analysis of specific chemical compositions of certain point in the reaction layer, the atom percent of Al and Fe was 68.92% and 23.56%, respectively. Therefore, the intermetallic compound mentioned above might be the mixture of Al_5Fe_2 and $Al_{13}Fe_4$ as stated below (as shown Fig. 6). The Cr and Ni as solute existed in the Al_5Fe_2 and $Al_{13}Fe_4$. Similar results have been obtained by Dybkov who has studied the reaction between 18Cr-10Ni stainless steel and liquid aluminum (973–1,123 K) in the immersion tests. Dybkov has determined that the reaction products are solid solution based upon the $Al_{13}Fe_4$ and Al_5Fe_2 [13].

According to Fe-Al equilibrium phase diagram [14], six non-stoichiometric intermeatllic componds of $AlFe_3$, AlFe, Al_2Fe, Al_3Fe_2, Al_5Fe_2, and $Al_{13}Fe_4$ possibly form during reaction between iron and aluminum. However, the $Al_{13}Fe_4$ and Al_5Fe_2 were only detected in this study. This is considered to be due to the formation thermodynamics and growth kinetics of the Fe–Al system intermeatllic compond. Generally, the generation of phase with low free energy is easy according to thermodynamic principles. Low free energy of $Al_{13}Fe_4$ is considered to be reason for its formation [3]. On the other hand, the fast growth of Al_5Fe_2 is reason for its formation although the free energy of phase Al_5Fe_2 is higher than that of $Al_{13}Fe_4$. There are a large number of aluminum vacancies along the *c*-axis of the orthorhombic structure of Al_5Fe_2. Along the *c*-axis, therefore, fast diffusion of active element occurred, thus resulted in the fast growth of Al_5Fe_2 [3].

Figure 5 shows the effects of welding time on the reaction layer thickness and the tensile shear strength of the joint welded at the welding temperature of 525°C. Meanwhile, it also represents the relationship between the tensile shear strength of the joint and reaction layer thickness at the interface. As shown, with the increasing of welding time, the tensile shear strength of the joint increased rapidly to 101.3 MPa. However, when welding time is more than 60 minutes, the strength of the joint began to decrease slowly. When welding time was 110 minutes, the value of the joint strength decreased to 72.3 MPa.

On the other hand, with the increasing of welding time, the reaction layer thickness monotonously increased. When the reaction layer thickness was approximately 0.8 µm, the value of the joint strength reached maximum. The results are basically consistent with the conclusion drawn by Kuroda Shinichi et al., who have welded A6061 aluminum alloy to SUS316 stainless steel using diffusion welding and investigated microstructure and properties of the butt joint [15]. They have claimed that the butt joint is strongest when the interfacial reaction layer is 1–2 µm [15]. The thinner reaction layer causes the diffusion and reaction inadequate, thus the joint strength decreases. However, more brittle intermetallic compounds appear in the interface of the joint when the reaction layer thickness is thicker, which makes the joint strength become lower. Therefore, thickness of reaction layer has important effects on properties of the joint and must be precisely controlled. The optimal reaction layer thickness was approximately 0.8 µm in this study.

In the recent literatures, electromagnetic impact welding and ultrasonic bonding as two important solid welding processes have been used to weld aluminum to stainless steel sheets and bond of 5052 to SUS304, respectively. The maximal strength of the joint by the former is approximately 43.0 MPa, and that of the joint by the latter is approximately 125.0 MPa [16, 17]. Compared with their results, the joint obtained in present study is enough powerful.

The observation results of morphology of the tensile shear fracture surface of aluminum alloy side revealed that there was silvery white and smooth thin film, which exposed that the fracture of the joint belonged to brittle fracture. The analysis of phase structure was conducted using X-ray diffraction (XRD) on tensile shear fracture surface of aluminum alloy side, and results are shown in Fig. 6. The new phases of Al_5Fe_2 and $Al_{13}Fe_4$ were detected on the tensile shear facture surface of aluminum alloy side. Detection of Al_5Fe_2 and $Al_{13}Fe_4$ illustrates

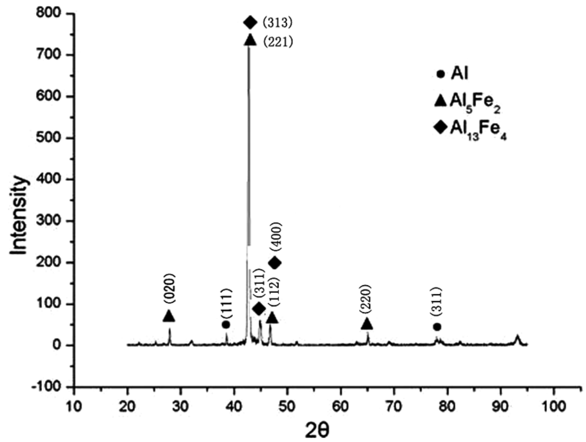

FIGURE 6.—XRD results of tensile shear fracture surface of aluminum alloy side.

the sample broke in the reaction layer. Therefore, the reaction layer is weak zone in the joint.

CONCLUSIONS

1. Direct diffusion bonded joint of aluminum alloy 5A02 and stainless steel SUS304 has been formed without any incorporating for no interlayer material.
2. Welding time has great effects on the tensile shear strength of the joint. When welding time was taken as 60 minutes, the strength of the joint achieved the maximum of 101.3 MPa.
3. The XRD analysis indicated the presence of intermetallic phases like Al_5Fe_2 and $Al_{13}Fe_4$ formed in the reaction. Microstructure investigation has revealed that the reaction layer thickness monotonously increased with the increasing of welding time.
4. The tensile shear strength of the joint is related to the reaction layer thickness. When the reaction layer thickness was approximately 0.8 μm, the value of the joint strength reached maximum.
5. Tensile testing of the joint reveals that the good mechanical property has been obtained after bonding at 525°C for 60 minutes duration.

ACKNOWLEDGMENTS

This work was supported by the Natural Science Research Project of the Education Department of Henan Province (2011A431003), the National Natural Science Foundation of China (U1204520), and the Basic Research Project of Henan Province (122300410202).

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