

Effects of Ni on microstructure and properties of aluminum-stainless steel TIG welding-brazing joint with Al-Si filler

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Abstract Effects of Ni on microstructure and properties of aluminum-stainless steel TIG welding-brazing joint with Al-Si filler were studied. Different mass percentage of Ni powder was added in the flux separately. Results of tensile tests show that a significant improvement on mechanical properties of the butt joint is obtained using the modified flux. Moreover, obvious differences on microstructures of the interfaces were observed with Ni addition, that two intermetallic compound (IMC) layers at the interface change to one layer and the IMC thickness also decreases. Finally, effect mechanism of Ni was analyzed and discussed. Ni addition leads to an enrichment of element Si at the brazing interface, and furthermore suppresses the formation of intermetallic compound. The reduction of IMC thickness is the main reason for the improvement of joint properties.

Key words aluminum alloy, stainless steel, welding-brazing, Nocolok, Ni, intermetallic

0 Introduction

The importance of weight reduction has increased substantially in the aviation and automotive industries over the past two decades. Aluminum-steel hybrid structures are expected to replace traditional steel designs for decreasing weight and fuel consumption, and at the same time, utilizing other unique properties of them. This trend can be expected to continue with the development of manufacturing.

However, there are many challenges when joining the two dissimilar metals. The large differences in thermal physical properties of them and the inevitable IMC formation make the welding very difficult^[1]. The IMC at the interface between aluminum and steel makes joint brittle, thereby resulting in significantly low strength and deformation.

In order to join the two materials, many solid state bonding technologies have been developed, such as friction welding^[2-6], friction stir welding^[7-12], explosive welding^[13] and diffusion bonding^[14-16]. However, there are a number of problems to be solved in applying these bonding techniques to mass production, from the view-

points of cost and productivity, e. g. shape limitations of the components, strict control of processing parameters and large plastic deformation in friction bonding^[17]. Many other welding processes have also been proposed for obtaining durable joints of aluminum-steel. Since the significant difference of their melting points and formation of many brittle intermetallic compounds illustrated in the binary system of iron-aluminum^[18], a welding process combining welding and brazing is more reasonable.

In the welding-brazing process for joining aluminum to steel, electron beam^[18], laser^[19] and electric arc^[20] are commonly used as heat sources. Although sound joints can be obtained with electron beam or laser, compared with the arc heat source, the complex facilities, costly welding equipments and the rigid workpiece assembly requirements limit their applications. Therefore, it is more promising to join the two dissimilar metals by the convenient and economical arc welding-brazing process.

During the welding-brazing process of aluminum to stainless steel, the filler metal is critical for the microstructure and properties of the joints. Various reports suggested that the addition of Si to molten aluminum signifi-

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cantly reduced the IMC formed in hot dipped aluminized steel^[21–22], and Al-Si alloy also has lower melting point together with good brazability, thus Al-Si filler has been widely used for joining aluminum to steel^[23–24]. However, the properties of the joints are not satisfactory because of the thick IMC. In order to improve the joint quality, different elements such as Cu and Mn have been studied for alloying the Al-Si system^[25–27] and obtained some positive results. The efforts were only focused on the optimization of brazing filler but not the flux at the brazing interface.

The purpose of present work is to study the influence of the addition of Ni on the microstructural characteristics and mechanical properties of aluminum to stainless steel joints with Al-Si filler.

1 Materials and methods

Base metals are 5A06 aluminium alloy and SUS321 stainless steel plates with 3.0 mm thickness. The filler wire utilized is ER4043 with diameter of 1.6 mm. The chemical compositions of the base materials and filler metal are shown in Table 1. The main compositions of the modified flux are Ni powder, non-corrosive Nocolok flux ($KAlF_4$ and K_3AlF_6 eutectic), and binder potassium sodium tartrate. The mass percentage of Ni powder in the flux is 20%, 30%, 35%, 40% and 50%, separately.

The size of specimen is 100 mm × 50 mm, and the surface was cleaned by abrasive paper and acetone before experiments. A single-V groove was prepared in the plates, with a bevel angle of 40° in steel side and 30° in aluminium side. The flux suspension with acetone was

smear homogeneously with 0.2–0.5 mm thickness on the groove and both front and back surfaces of the steel in 10 mm width. The schematic of the joining process with the flux is shown in Fig. 1. The TIG welding-brazing experiments were carried out using CLOOS GLW-300 welding source. The welding parameters were AC square wave of 100 Hz, welding current of 135 A with 2:1 AC balance, arc length of 3.0–4.0 mm, welding speed of 120 mm/min and argon gas flow rate of 8–10 L/min.

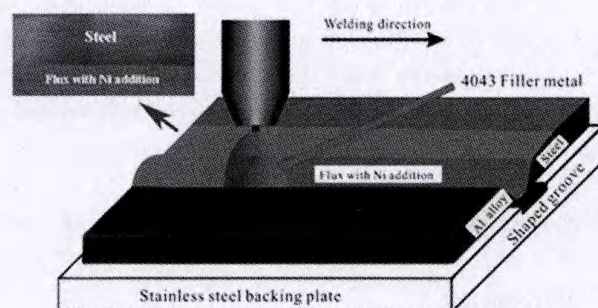


Fig. 1 The schematic of the joining process with flux containing Ni

Macrostructure of the joint was observed by optical microscope after polished and etched with Keller's reagent. Microstructures and compositions of IMCs were observed and analysed by scanning electron microscopy (SEM) together with energy dispersive spectrometer (EDS). Tensile test was conducted by INSTRON-5569 testing machine, with loading rate of 1 mm/min. All tests were repeated at least three times.

Table 1 Chemical compositions of base materials and filler metal (wt.%)

Materials	C	Mn	Mg	Al	Si	Cu	Ti	Ni	Cr	Fe
SUS321	0.1	2	—	—	1	—	0.2	8–11	17–19	Balance
5A06	—	0.5–0.8	5.8–6.8	Balance	0.4	0.1	0.1	—	—	0.4
ER 4043	—	<0.15	<0.20	Balance	4.5–6.0	<0.30	<0.15	—	—	<0.6

2 Results and discussion

2.1 Macrostructure and appearance

Fig. 2 shows the appearance of aluminum-steel butt joint processed by TIG welding-brazing with Al-Si filler. Good front and back formations were obtained with the

help of the flux, and no crack or undercut was observed. The residual Nocolok and Ni powder on the steel surface after welding can be removed easily.

Fig. 3 is the typical cross-section of aluminum-steel joint with both welding and brazing features. The alumi-

num alloy with low melting point was fused and mixed with the liquid filler metal to produce the welded seam. It has obvious fusion zone and exhibits complete fusion on the side of aluminum, while the stainless steel keeps in solid state and joins the seam based on the interaction between solid stainless steel and liquid Al-Si filler metal.

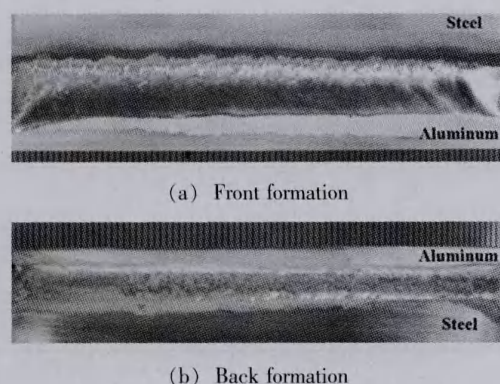


Fig. 2 Appearances of the aluminum-steel joint

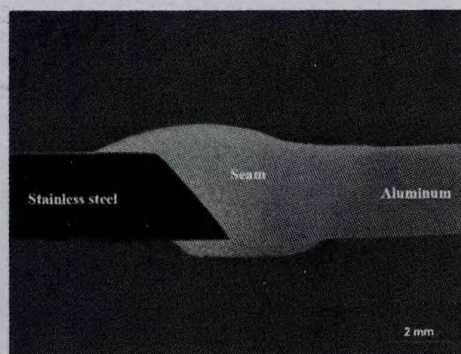


Fig. 3 Typical cross-section of the aluminum-steel butt joint

2.2 Effect of Ni addition on mechanical property

Tensile tests were carried out to evaluate the tensile strength of the joints. As shown in Fig. 4, the strength of the joint improves with the increase of the mass percentage of Ni in the flux until it reaches 35%. The maximum increasing range of the strength value is about 63 MPa (77%), from 82 MPa to 145 MPa.

There is an optimum proportion of Nocolok to Ni powder on both formation and property aspects. To get good weld bead formation, essential proportion of Nocolok (above 30 wt.%) is required to realize the wetting and spreading of molten aluminum on steel. To obtain good

property of the joint, 35 wt.% of Ni powder in the flux has been proved the best proportion. Therefore, the comparison of microstructure was then conducted between the joints using the flux containing 0wt.% and 35wt.% Ni powder.

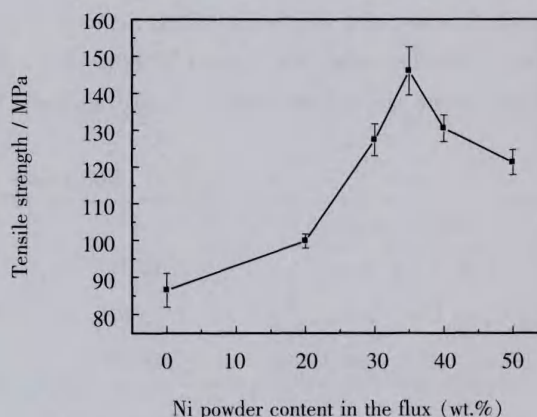


Fig. 4 Relationship between Ni powder content and tensile strength of the joints

2.3 Effect of Ni addition on microstructure and elements distribution

The microstructure and composition of intermetallic compounds analysis was carried out by SEM-EDS. As shown in Fig. 5, there are two intermetallic layers at the Al-steel interface using 100% Nocolok, while only one intermetallic layer is observed when using the flux with 35 wt.% nickel powder, and the IMC thickness of the latter is much thinner. Besides, the morphology of the precipitate phases in the welded seam is much smaller and more dispersive when the Ni powder was added.

Combining the EDS results in Table 2 with the Al-Fe binary and Al-Fe-Si ternary phase diagrams, the intermetallic layers could be identified as the Fe-Al-Si ternary phase or the Fe-Al binary phase with silicon element dissolving in solid solution. According to the existing research^[24], the layer I IMC near the stainless steel substrate in the SEM photomicrograph should be θ -Fe₄Al₁₃, and layer II near the welded seam should be τ_5 -Fe₂Al₈Si.

According to Table 2, all IMC layers contain some Cr and Ni elements but more Ni content was detected in layer II with Ni addition in the flux. Moreover, the silicon con-

tent in the layer II with the addition of Ni powder in the flux is much higher. This phenomenon is also exhibited by the EDS results of linear scanning on the interface of aluminum and steel in Fig. 6.

Fig. 7 shows the distribution of major alloy elements near the interface. It can be seen that all the main elements such as Fe, Cr, Ni, Si and Al participated in the reaction of IMC formation. Fe, Cr and Ni diffused into the interfacial layers and welded seams. Si also appeared in

these zones too. The enrichment of Si can also be observed in the maps with Ni addition. The enriched Si distributed mainly along the boundary of the IMC.

Table 3 displays EDS results of precipitate phases in the welded seams. Higher Ni element content was observed in the precipitate phases of the joint using the flux with Ni addition. This increase of Ni content should be attributed to the Ni in the flux but not the dissolution of stainless steel.

Table 2 EDS results of different IMC layers (wt.%)

Interface layers	Al	Si	Fe	Cr	Ni
Layer I with Nocolok	54.71	4.76	29.85	8.28	2.40
Layer II with Nocolok	63.62	7.05	23.98	4.47	0.88
Layer II with Nocolok and Ni	58.17	16.72	17.42	5.67	2.01

Table 3 EDS results of precipitate phases in welded seams (wt.%)

	Al	Si	Fe	Cr	Ni
Joint with Nocolok	86.41	4.97	6.92	1.15	0.54
Joint with Nocolok and Ni	80.53	9.19	6.20	0.77	3.31

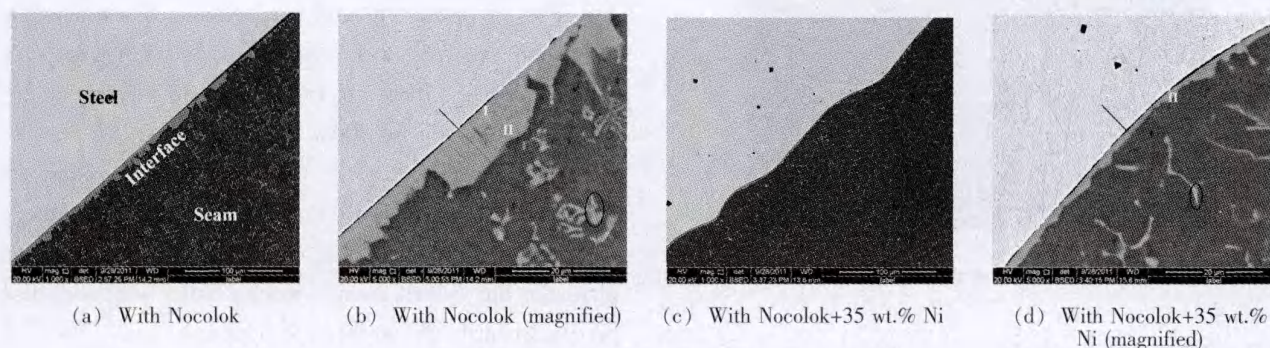


Fig. 5 SEM photomicrograph of the interface of the aluminum and steel

2.4 Effect mechanism of Ni addition

The austenitic stainless steel in this study is composed of three major elements Fe, Cr and Ni. Compared with Fe and Cr, Ni has the highest solubility in liquid aluminum according to the former research^[28], which can achieve 31 wt.% at 900 °C. During TIG welding-brazing process, the Nocolok flux firstly melted under the arc heat and the Ni powder deposited on the surface of the steel before the aluminum pool arrived. When solid steel coated

with molten flux contacted to the aluminium pool, the molten aluminium spread quickly with the help of the liquid flux. At the same time, Ni powder firstly acted as a chemical barrier and dissolved into the liquid aluminum, as shown in Fig. 8a, and then the concentration of Ni near the interface increased, while the Si in molten aluminium moved more or faster to the interface because of the Ni addition, as exhibited in Fig. 8b. With the diffusion of elements, flow of weld pool and decline of temperature, only

one IMC layer formed because the Si enrichment at the interface, while Ni from the flux, Fe, Cr, Ni dissolved from the stainless steel together with Si and Al from the filler formed fine and dispersive precipitate phase in the welded

seam, as shown in Fig. 8c. Therefore, with Ni addition in the flux, Si enrichment at the interface led to the suppression of IMC layers, and furthermore improved the property of the joint.

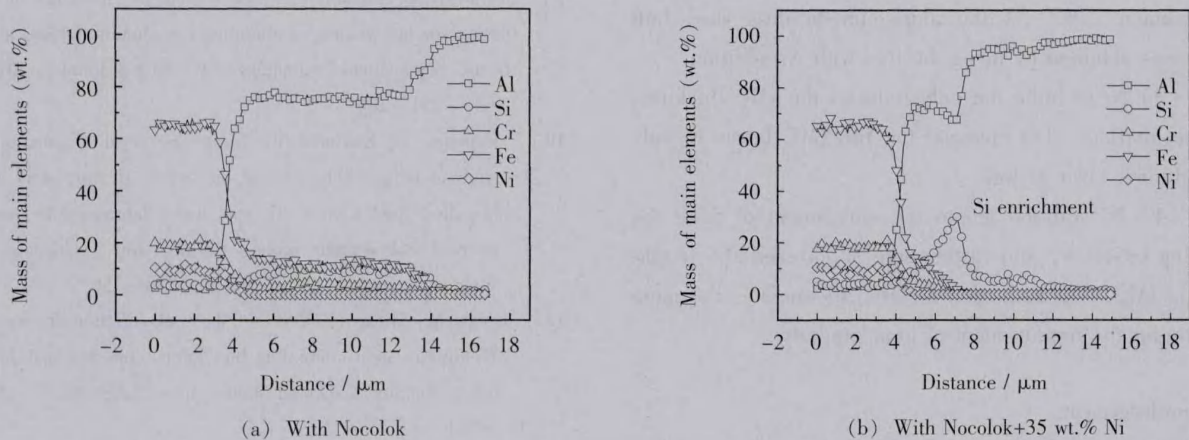


Fig. 6 EDS analysis results of linear scanning

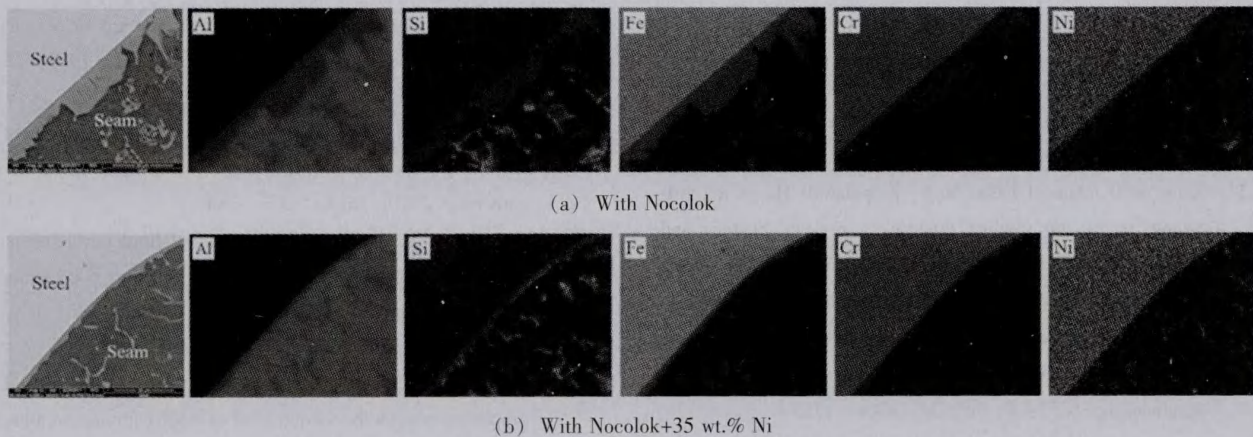


Fig. 7 EDS compositional maps of element Al, Si, Fe, Cr and Ni near the interface

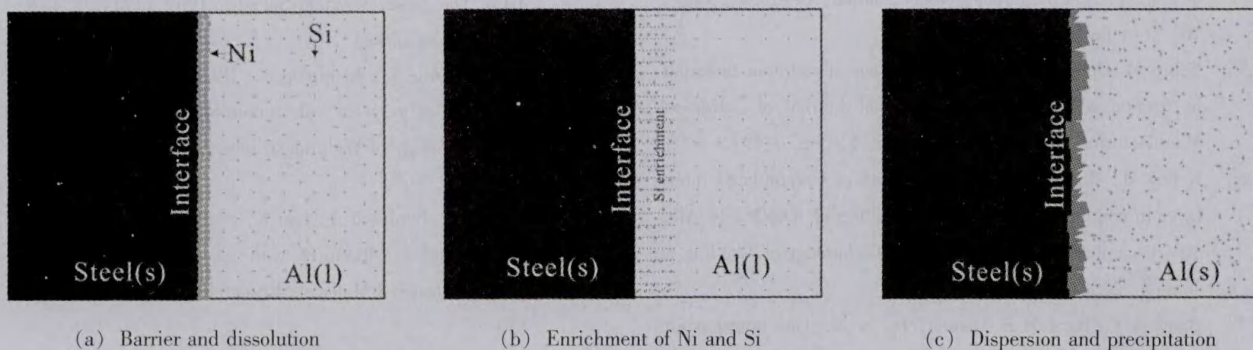


Fig. 8 Schematic of the effects of Ni powder addition during TIG welding-brazing process

3 Conclusions

(1) Ni powder was added to the Nocolok flux for alloying the brazing interface and welded seam of aluminum-steel joint.

(2) A significant improvement on tensile strength (maximum 77%) of the aluminum-stainless steel butt joint was obtained by using the flux with Ni addition.

(3) Ni addition not only reduced the IMC thickness at the interface, but changed the two IMC layers to only one thinner layer as well.

(4) Ni addition led to the enrichment of Si at the brazing interface, and furthermore suppressed the formation of IMC. The reduction of IMC thickness is the main reason for the improvement of joint property.

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