Laser and Gas Metal Arc Based Dissimilar Joining of Automotive Aluminium Alloys and Steel Sheets - A Review

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Abstract

Multi-material joining of aluminium to steel is mainly restricted due to their different thermo-physical properties, melting temperatures, low solubility and in particular, formation of brittle intermetallic phase layer at the joint interface. Various joining processes have been attempted to join aluminium and steel sheets with an aim to reduce the growth of phase layer by precise control of heat input. However, laser beam and arc based joining processes are popular among other joining processes due to their strict control of heat input with regulative metal transfer and flexibility to join intricate shapes. A critical survey in joining aluminium to steel sheets by laser beam and arc based joining processes are presented in the present work. The influence of various joining parameters such as heat input, filler wire types on the growth of intermetallic phase layer thickness and corresponding joint strength are analysed and reported subsequently.

Key Words : Laser beam welding, Gas metal arc welding, Aluminum alloy, Galvanized steel

1. Introduction

Joining of multi-material combinations such as aluminium to steel has gained significant attention in the automotive industry as a recourse to enhance the strength-to-weight ratio of the vehicle structures¹⁻⁵. However, aluminium to steel joining is remain challenging due to their diverse thermo-physical properties, varying melting temperatures, poor solubility of aluminium in iron and in particular, formation of intermetallic phase layer with several Fe-Al brittle intermetallic compounds (IMC)⁶. Although presence of intermetallic phase layer is needed for the joint to form, however formation of thicker phase layer leads to embattlement of the joint⁵⁻⁷. Experimental studies indicate stringent control of the heat input is required to reduce the extent of formation of phase layer during joining of aluminium alloys and galvanized steel sheets⁷.

Various processes such as resistance spot welding (RSW)⁸, friction stir welding (FSW)⁹, laser beam^{10,11} and arc^{6,7,12-15} based joining techniques are attempted to join aluminium and steel with an aim to keep the heat input significantly low. Joining of complex contours us-

ing FSW remained a problem while severe electrode wear due to chemical reaction between copper electrode and aluminium alloys inhibited use of RSW process in joining of aluminium alloys as well as of aluminium and steel^{9,16}. The use of laser and advanced pulsed current arc based joining processes is increasing in recent times due to their superior control over heat input with metal transfer rate, and flexibility to join out-of-position geometries^{5-7,10,11}.

2. Motivation

Laser beam and pulsed current gas metal arc (GMA) based techniques could join thin metallic sheets of dissimilar materials at a very low power with moderate to reasonable high speed. The recently reported studies on application of laser beam and GMA based processes for joining of aluminium to steel sheets involved primarily the assessment of growth of intermetallic phase layer thickness with nature of IMCs at the joint interface and the corresponding joint strengths^{6,7,10,11}. Laser beam and GMA based processes commonly employed pure Al, Al-Si, Al-Mg filler wires as well as without filler wire in joining aluminium to steel sheets^{5-7,10-14}. Several

authors found phase layer thickness in the range of $0.9 \sim 30 \mu\text{m}$ with corresponding joint strength around $80 \sim 201 \text{ MPa}$ using pure Al, Al-Si, Al-Mg filler wires^{7,10-12,14,15}. In another case, a heat input of 200 J mm^{-1} generated the phase layer thickness in the range of $3 \sim 5 \mu\text{m}$ with maximum joint strength around 200 MPa ⁶. Most of the available studies reported usage of different types of filler wires with widely varying range of the heat input and phase layer thickness to obtain a sound and defect-free joint. In the present study, the current applications of laser beam and GMA based joining processes to make a suitable joint between aluminium alloys and different types of steel sheets are presented. The influence of joining parameters such as heat input, filler wire types and varieties of steel surface coating on growth of phase layer at the joint interface and corresponding joint strength are illustrated further in details.

3. Laser Beam Based Joining

Mathieu et al.¹⁷ used typical heat input range of $50 \sim 60 \text{ J mm}^{-1}$ in laser beam joining of aluminium alloy to hot-dip galvanized (GI) steel sheets with Zn-15%Al filler wire. The authors reported the formation of phase layer thickness around $5 \mu\text{m}$ with joint strength of $190 \sim 230 \text{ N mm}^{-1}$. A nearly similar filler wire composition was used by Dharmendra et al.¹⁸ to join 1.2 mm thick AA6016 alloy to 0.77 mm thick GI steel sheets following heat input range of $30 \sim 180 \text{ J mm}^{-1}$. Fig. 1 shows that authors achieve maximum joint strength around 200 MPa for a heat input range of $60 \sim 110 \text{ J mm}^{-1}$ by containing the phase layer thickness within $8 \sim 12 \mu\text{m}$ ¹⁸. While, Shabadi et al.¹⁹ used a heat input of 45 J mm^{-1} to join 1.2 mm thick AA6016 alloy and 0.7 mm thick

Fig. 1 Variation of heat input, joint strength and phase layer thickness in laser beam joining of aluminium alloy and steel sheets¹⁸. Heat input and joint strength are marked by circle and square, respectively

GI steel sheets by laser beam based process using Zn-30%Al filler wire. The phase layer thickness was found to be within $10 \mu\text{m}$ with maximum joint strength of 190 MPa ¹⁹.

Other authors used Si-based filler wire to join aluminium and steel sheets using laser beam due to their wider availability and ease of use. Sierra et al.¹⁰ joined 1 mm thick AA6016 alloy to 1.2 mm thick GI steel sheet using a laser beam with AA4047 (Al-12%Si) filler wire considering a heat input range of $120 \sim 150 \text{ J mm}^{-1}$. The authors found phase layer thickness around $2 \mu\text{m}$ and the maximum joint strength was 190 MPa ¹⁰. While, Zhang et al.²⁰ reported phase layer thickness in the range of $1.5 \sim 13 \mu\text{m}$ with the maximum joint strength of 162 MPa in joining of 1.15 mm thick AA6016 alloy and 1.2 mm thick GI sheets by AA4043 (Al-5%Si) filler wire using heat input range of $138 \sim 156 \text{ J mm}^{-1}$. A similar filler wire composition was used by Qin et al.^{21,22} to join 1 mm thick AA6013 alloy and 2 mm thick GI steel sheets using a laser-GMA hybrid process. The phase layer thickness was restricted within $2 \sim 4 \mu\text{m}$ and maximum joint strength was found to be around 247 MPa ²¹.

Saida et al.²³ used the tandem laser beam process for joining of 1.2 mm thick AA6022 alloy and 0.8 mm thick GI and galvanized (GA) steel sheets with AA4047 filler wire. The authors found maximum joint strength of 180 N mm^{-1} with phase layer thickness around $2 \sim 3 \mu\text{m}$. Yang et al.²⁴ used heat input of around $70 \sim 168 \text{ J mm}^{-1}$ to join 2 mm thick AA5754 alloy and 1 mm thick galvanized DP980 steel sheets by diode laser beam using AA4047 filler wire. Fig. 2 shows variation of joint strength as a function of heat input. The authors reported poor joint strength of 118 N mm^{-1} at a low heat input of 70 J mm^{-1} , which was attributed to inadequate wetting of filler deposit on steel surface. At a medium heat input of 120 J mm^{-1} , the joint strength was

Fig. 2 Influence of heat input on joint strength in laser beam joining of AA5754 alloy and galvanized DP980 steel sheets²⁴

improved to 220 N mm^{-1} due to enhancement of wettability of filler deposit on the steel surface, and maximum heat input of 168 J mm^{-1} resulted in formation of greater amount of brittle intermetallic compounds and consequently reduced the joint strength to 137 N mm^{-1} . Sun et al.^{25,26)} employed AA4043 filler wire to join 2.5 mm thick AA6061 alloy and electrogalvanized steel sheets by fiber laser beam in butt joint configuration. The authors reported to contain the phase layer thickness in the range of $1.8 \sim 6.2 \text{ }\mu\text{m}$ with joint strength of 174.64 MPa ^{25,26)}.

Thomy et al.¹¹⁾ used heat input range of $47 \sim 56 \text{ J mm}^{-1}$ to join 1.15 mm thick AA6016 alloy and 1 mm thick DC05 galvanized steel sheets by laser-GMA hybrid source using AA4047 filler wire. The authors found phase layer thickness around $4 \sim 12 \text{ }\mu\text{m}$ and the maximum joint strength of 180 MPa ¹¹⁾. Gao et al.²⁷⁾ joined AA6061 alloy to AISI304 stainless steel, both of 2 mm thickness, using laser-CMT hybrid technique with AA4047 filler wire. The authors found that a heat input range of $80 \sim 110 \text{ J mm}^{-1}$ could contain the phase layer thickness within the range of $3 \sim 6.5 \text{ }\mu\text{m}$ with the maximum joint strength of 130 MPa ²⁷⁾.

In contrast to the laser-GMA hybrid process, Yan et al.²⁸⁾ employed both continuous and pulsed mode dual laser beam for joining of 1.2 mm thick AA6111 alloy and 0.8 mm thick low carbon steel sheets without any filler wire, and found the layer thickness around $10 \text{ }\mu\text{m}$ with the maximum joint strength of 128 MPa . In another study, Frank²⁹⁾ used a combined pulsed and continuous laser beam to join 1 mm thick aluminium alloy and 0.75 mm thick GI sheets in both lap and flange joint configurations by AA4043, AA4047 and Zn-12%Al filler wires. The author reported maximum joint strength in the range of $180 \sim 220 \text{ MPa}$ with all three types of filler wires in both the lap and the flange configurations. Ma et al.³⁰⁾ attempted to join 1 mm thick AA6061 alloy and 0.8 mm thick galvanized DP590 steel using a two-pass laser beam technique without any filler wire. The authors could contain the phase layer thickness around $5 \text{ }\mu\text{m}$ with maximum joint strength of 158 N mm^{-1} . While, Windmann et al.³¹⁾ used a Al-Si3-Mn filler wire to join both 1.5 mm thick AA6016 alloy and aluminized steel sheets considering a higher heat input range of $240 \sim 330 \text{ J mm}^{-1}$. The maximum joint strength was reported to be 175 MPa for phase layer thickness of $2 \sim 7 \text{ }\mu\text{m}$ ³¹⁾. In contrast, Borrisutthekul et al.³²⁾ reported wider range of heat input of $225 \sim 900 \text{ J mm}^{-1}$ in laser beam lap joining of 1.6 mm thick AA6022 alloy to 1.2 mm thick steel sheets using different backing plates. Pardal et al.³³⁾ spot welded 1 mm thick AA6111 alloy and DC04 uncoated low carbon steel sheets using conduction mode

defocused laser beam in lap joint geometry. The authors reported to contain layer thickness around $10 \text{ }\mu\text{m}$ with maximum joint strength of 130 MPa . Huang et al.³⁴⁾ joined 2 mm thick 5A02 alloy and 1 mm thick GI steel sheets without any filler wire by laser-GTA hybrid process. The maximum joint strength was found to be around 163 MPa at phase layer thickness of $8.7 \text{ }\mu\text{m}$ and corresponding heat input of 136.8 J mm^{-1} . In another study, Cui et al.³⁵⁾ employed dual laser beam for joining low carbon steel and AA6061 alloy, both of 1.5 mm in thickness, without any filler wire. The authors reported the maximum joint strength of 110.6 N mm^{-1} with the separation distance between the laser beam as 1.5 mm and power distribution ratio as 0.67 ³⁵⁾. Table 1 shows the ranges of employed heat input, growth of phase layer thickness and achieved joint strength in joining of aluminium to steel sheet by laser beam based and laser - arc hybrid processes.

4. Gas Metal Arc Based Joining

Several researchers have attempted joining of aluminium and steel sheets using pulsed current GMA based process using Al-Si filler wires. Murakami et al.¹²⁾ used a flux cored AA4047 filler wire to join 2 mm thick pure aluminium alloy and uncoated steel sheets using a heat input range of $170 \sim 255 \text{ J mm}^{-1}$. The maximum joint strength was reported to be 80 MPa with phase layer thickness around $0.9 \sim 2.5 \text{ }\mu\text{m}$ ¹²⁾. Park et al.³⁶⁾ used AC pulsed GMA process to join 1.4 mm thick uncoated steel and 1.6 mm thick AA6K21 alloy by AA4043 filler wire. The phase layer thickness was contained within $1.14 \sim 3.2 \text{ }\mu\text{m}$ and the maximum joint strength was achieved as 173 MPa ³⁶⁾.

Su et al.^{13,14)} examined the effect of four different filler wires - pure aluminium, AA4043, AA4047 and AA5356 (Al-5%Mg) wire - to join AA5052 alloy and GI steel sheets, both in 1 mm thickness, using a AC double-pulsed GMA technique with heat input of 111 J mm^{-1} . Pure aluminium and Al-Mg filler wires exhibited a constant phase layer thickness of around $30 \text{ }\mu\text{m}$ ¹⁴⁾. The layer thickness reduced to $1 \sim 7 \text{ }\mu\text{m}$ when Al-Si filler wires were used^{13,14)}. The joints made with the pure aluminium and Al-Mg filler wires exhibited lower failure strengths of respectively 165 and 112 MPa , and the same with the Si-based wires was around 201 MPa ^{13,14)}. In another study, Shi et al.^{37,38)} and Shao et al.³⁹⁾ used pulsed current double-electrode GMA technique to examine the effect of AA4043 and AA5356 filler wires in joining both of 1 mm thick AA5052 alloy and GI sheets. The maximum joint strength with the Al-Si filler wire was reported to be around 199 MPa ³⁷⁾. The joints

Table 1 The ranges of employed heat input, growth of phase layer thickness and achieved joint strength in joining of aluminium to steel by laser beam based and laser-arc hybrid joining processes

Process	Al Alloy, t_{Al} (mm)	Steel, t_{st} (mm)	H.I (J mm ⁻¹)	Filler wire	d_p (μ m)	Strength	Reference
Laser	AA6016, 1	GI, 1.2	102 ~ 150	AA4047	2	190 MPa	Sierra et al. ¹⁰⁾
	Al alloy	GI	50 ~ 60	Zn-15%Al	5	193 ~ 230 N mm ⁻¹	Mathieu et al. ¹⁷⁾
	AA6016, 1.2	GI, 0.77	60 ~ 110	Zn-15%Al	8 ~ 12	200 MPa	Dharmendra et al. ¹⁸⁾
	AA6016, 1.2	GI, 0.7	45	Zn-30%Al	10	190 MPa	Shabadi et al. ¹⁹⁾
	AA6016, 1.15	GI, 1.2	138 ~ 156	AA4043	1.5 ~ 13	162 MPa	Zhang et al. ²⁰⁾
	AA6022, 1.2	GI and GA, 0.8	-	AA4047	2 ~ 3	180 N mm ⁻¹	Saida et al. ²³⁾
	AA5754, 2	DP980, 1	70 ~ 168	AA4047	-	137 ~ 220 N mm ⁻¹	Yang et al. ²⁴⁾
	AA6061, 2.5	Electro-GI, 2.5	-	AA4043	1.8 ~ 6.2	174.64 MPa	Sun et al. ^{25,26)}
	AA6111, 1.2	Low carbon, 0.8	-	-	10	128 MPa	Yan et al. ²⁸⁾
	Al alloy, 1	GI, 0.75	-	AA4043, AA4047, Zn-12%Al	-	180 ~ 220 MPa	Frank ²⁹⁾
	AA6061, 1	DP590, 0.8	-	-	5	158 N mm ⁻¹	Ma et al. ³⁰⁾
	AA6016, 1.5	Aluminized steel, 1.5	240 ~ 330	Al-Si3-Mn	2 ~ 7	175 MPa	Windmann et al. ³¹⁾
Laser-spot	AA6111, 1	Uncoated DC04, 1	-	-	10	130 MPa	Pardal et al. ³³⁾
Laser-GMA hybrid	AA6016, 1.15	DC05, 1	47 ~ 56	AA4047	4 ~ 12	180 MPa	Thomy et al. ¹¹⁾
	AA6013, 1	GI, 2	-	-	2 ~ 4	247 MPa	Qin et al. ^{21,22)}
	AA6061, 2	AISI304, 2	80 ~ 110	AA4047	3 ~ 6.5	130 MPa	Gao et al. ²⁷⁾
Laser-GTA hybrid	5A02, 2	GI, 1	136.8	-	8.7	136.8	Huang et al. ³⁴⁾

H.I - Heat input, d_p - phase layer thickness, t_{Al} - aluminium sheet thickness, t_{st} - steel sheet thickness

that were made with the Al-Mg filler wire had resulted in higher thickness of phase layer as compare to that achieved with the Al-Si filler wire and lower joint strength of 188 MPa³⁷⁾.

Several researchers also studied the effect of galvanized coating on the quality of pulsed current GMA based joining of aluminium alloys and coated steel sheets. Yagati et al.⁴⁰⁾ joined 2 mm thick AA6061 alloy and 1.2 mm thick GI, GA and uncoated steel sheets using a heat input of 62.75 J mm⁻¹ with AA4043 filler wire. The joint strength with the GI sheets was reported around 180 N mm⁻¹ as compared to 120 and 110 N mm⁻¹ respectively with the GA and uncoated steel sheets⁴⁰⁾. The authors attributed the lower phase layer thickness and greater joint strength for the GI steel sheets due to the superior wetting on unmelted steel sheets⁴⁰⁾. While, Zhang and Liu¹⁵⁾ studied joining of aluminium alloy to hot-dip aluminized and GI stainless steel sheets, all in 1 mm thickness, by pulsed current GMA technique using AA4043 filler wire with suitable ranges of heat input of 63 ~ 120 J mm⁻¹. The aluminium to GI steel joints exhibited a continuous bead, whereas the aluminium and the aluminized steel sheets failed to produce any joint¹⁵⁾. Fig. 3 shows variation of heat input and joint strength in GMA joining of aluminium to GI

sheets as reported in Ref. [15]. Fig. 3 illustrates joint strength is increasing from 168 to 194 MPa with an increase in heat input from 63 to 86 J mm⁻¹. Further increase in heat input to 120 J mm⁻¹ reduced strength to 169 MPa. The joints with the GI sheets exhibited phase layer thickness around 5 ~ 15 μ m with maximum joint strength of 194 MPa, while layer thickness of 10 μ m with failure strength of 60 MPa was found with the alu-

Fig. 3 Comparison of heat input and joint strength in GMA joining of aluminium to GI sheets¹⁵⁾

Fig. 4 The current and voltage waveform of CMT process⁴¹⁾

minized steel sheets¹⁵⁾.

Zhang et al.⁴¹⁾ used Cold Metal Transfer (CMT), a pulsed current GMA technique with short-circuiting metal transfer, to join 1 mm thick AA1060 and 0.6 mm thick GI sheets in lap joint configuration using AA4043 filler wire. Fig. 4 depicts the current and voltage transients in a typical CMT process as reported by the authors⁴¹⁾. Following points are worth noting from Fig. 4⁴¹⁾.

- The peak current phase is represented by a constant arc voltage and a high current pulse that was envisaged to facilitate the formation of a droplet at the tip of filler wire,
- In the background phase, the current was reduced and kept constant till the beginning of the short-circuiting period to decrease the arc power and inhibit globular transfer of droplet from the filler wire tip,
- During the short circuiting phase the filler wire dipped into the melt pool causing the arc to extinguish and the voltage reduced to zero. A backward movement of the filler wire at this stage is provided to assist the detachment of the droplet from the filler wire into the melt pool without the aid of electromagnetic force. The arc reignite at the end of short circuiting phase⁴¹⁾.

The authors reported phase layer thickness around 4 μm with maximum joint strength of 83 MPa⁴¹⁾. Agudo et al.⁵⁾ used the CMT process to join 1 mm thick AA6016 alloy and hot dip galvanized steel sheets with AA1080 (Al-99.8%) filler wire and found phase layer thickness of 2.3 μm at the joint interface. In another study, Zhang et al.^{42,43)} used AA4043 filler wire to join both of 1 mm thick aluminium alloy and GI sheets by the CMT process with a heat input range of around 55 ~ 91 J mm⁻¹. The authors reported phase layer thickness around 7 ~ 40 μm and achieved the maximum joint strength of 96 MPa^{42,43)}. Cao et al.⁶⁾ achieved a smooth joint bead in joining of AA6061 alloy and GI sheets, both in 1 mm

thickness, using the CMT process with AA4043 filler wire and higher heat input of 200 J mm⁻¹. The authors achieved maximum joint strength of 200 MPa by containing the phase layer thickness within 3 ~ 5 μm ⁶⁾. Kang and Kim⁴⁴⁾ employed typical heat input of 112 J mm⁻¹ to join AA5052 alloy with hot dip aluminized and with GI steel sheets in the thickness ranges of 1 to 1.2 mm by CMT process using AA4043, AA4047, AA5183 and AA5356 filler wires. The authors found phase layer thickness around 5 μm with Al-Si filler wire while the Al-Mg filler wire resulted in higher the phase layer thickness of 12 ~ 13 μm ⁴⁴⁾.

Das et al.^{7,45,46)} used a wide range of heat input from 36 ~ 126 J mm⁻¹ for joining of aluminium alloy to GI and GA steel sheets by *coldArc*, a low heat input pulsed current GMA process. Fig. 5 shows the current and voltage waveform of *coldArc* process and following points are noting⁷⁾

- The short-circuiting period (t_s) began with rapid increase in welding current and drop of voltage to a very small value.
- At the end of the short-circuiting period, the current was reduced to a small value to shear-off the molten metal from liquid bridge at a low power resulting in reduction of spatter.
- In arcing period (t_A), a peak current pulse was applied for a very short duration to facilitate the formation of droplet at the tip of filler wire. Current was reduced further and kept constant until the droplet formed a liquid bridge with molten pool.

The authors found a profound dependence of heat input with phase layer thickness and joint strength. Fig. 6 shows variation of phase layer thickness and joint strength with heat input in joining of AA5754 alloy and GI sheets. Fig. 6(a) shows phase layer thickness is increasing from 0.52 to 3.73 μm with rise in heat input from 36 to 68 J mm⁻¹. Fig. 6(b) depicts an increase in

Fig. 5 Current and voltage waveform of coldArc process⁷⁾

Fig. 6 Variation of heat input with (a) phase layer thickness and (b) joint strength in GMA joining of AA5754 alloy and GI sheets⁷⁾

heat input from 36 to 53 J mm⁻¹ increases corresponding joint strength from 188 to 206 MPa, and further rise in heat input decreases joint strength to 180 MPa⁷⁾. The authors found phase layer thickness around 1.3 ~ 2 μm with maximum joint strength of 73 MPa for aluminium to GA sheets^{45,46)}, while joining with GI sheet exhibited higher joint strength of 210 MPa with phase layer thickness of 0.8 ~ 4.5 μm⁷⁾.

Milani et al.⁴⁷⁾ examined the influence of different filler wires - AA4043, AA4047 and Al-Si3-Mn - on joining of 2 mm thick AA5754 alloy and 3 mm thick GI steel sheets by CMT process. The maximum joint strength was found to be around 188 MPa with the Al-Si3-Mn1 filler wire⁴⁷⁾. In another study, Chang et al.⁴⁸⁾ investigated the effect of AA2319 (Al-6%Cu) and AA5087 (Al-5%Mg) filler wire on joint quality in joining of AA6082 and ultra-high strength steel, both of 4 mm in thickness, by GMA process. The authors found Al-Cu filler wire exhibited lower phase layer thickness around 2 ~ 4 μm while Al-Mg filler wire resulted layer thickness of 6 ~ 18 μm⁴⁸⁾. The maximum joint strength was reported to be around 128 MPa using Al-Cu filler wire⁴⁸⁾.

Ma et al.⁴⁹⁾ employed different pre-heating temperature to join 1 mm thick AA5052 alloy and 2 mm thick GI sheet by pulsed current GMA process using heat input range of 54.6 ~ 110.5 J mm⁻¹ and AA4043 filler wire. The author reported pre-heating temperature had direct influence on growth of phase layer thickness. The authors found phase layer thickness in the range of 1 ~ 10 μm and achieved maximum joint strength around 162 MPa for pre-heat temperature of 373 K⁴⁹⁾. Madhavan et al.⁵⁰⁾ used heat input range of 110 ~ 140 J mm⁻¹ for joining 2 mm thick AA6061 alloy and 1.6 mm thick DP800 steel sheets by CMT process with AA4043 filler wire. The corresponding phase layer thickness and the maximum

joint strength were reported to be 1.23 ~ 3.02 μm and 440 N mm⁻¹, respectively⁵⁰⁾.

Ye et al.^{51,52)} achieved excellent joint bead using GMA-GTA double sided arc process in joining AA5052 alloy and low carbon steel, both of 3 mm in thickness, with AA4043 filler wire and considering heat input of 85.8 J mm⁻¹. The author found lower layer thickness of 2.03 μm using double sided arc process while conventional GMA process exhibited layer thickness of 4.03 μm. The maximum joint strength in double sided arc process was reported to be 148.1 MPa, which was 2.5 times than that of the traditional GMA process⁵¹⁾. Table 2 illustrates a brief summary of heat input and filler wire composition on the joint strength and formation of intermetallic phase layer in GMA based joining of aluminium and steel sheets.

Experimental investigations on joining of aluminium to steel sheets by laser beam, laser-arc hybrid and GMA based joining processes with different filler wire compositions are presented. The best joint strength could be achieved with a relatively thinner phase layer. The heat input and composition of filler wire were reported to be a crucial factor to control the growth of the phase layer. Furthermore, the Zn coating in case of galvanized sheets could improve the wetting of the filler wire deposit on the unmelted steel surface and the joint strength.

5. Influence of Heat Input on Intermetallic Phase Layer Thickness and Joint Strength

A direct effect of heat input on the formation of thicker phase layer is generally agreed in most of the experimental studies in joining of aluminium and steel using laser beam and GMA based processes. However, the suggested range of heat input for controlling the phase layer thicknesses also varied in the published literature. For example, a heat input range of 47 ~ 110 J mm⁻¹ was

Table 2 Applied heat input, intermetallic phase layer thickness and corresponding joint strength in joining of aluminium to steel by GMA based joining process

Process	Al Alloy, t_{Al} (mm)	Steel, t_{st} (mm)	H.I (J mm ⁻¹)	Filler wire	d_p (μm)	Strength	Reference
Pulsed GMA	Al alloy, 2	Uncoated steel, 2	170 ~ 255	AA4047	0.9 ~ 2.5	80 MPa	Murakami et al. ¹²⁾
	Al alloy, 1	GI, 1	63 ~ 120	AA4043	5 ~ 15	168 ~ 194 MPa	Zhang and Liu ¹⁵⁾
	AA5052, 1	GI, 1	-	AA4043, AA5356	-	199 MPa (AA4043), 188 MPa (AA5356)	Shi et al. ^{37,38)} , Shao et al. ³⁹⁾
	AA6061, 2	GI, GA and uncoated steel, 1.2	62.75	AA4043	-	110 ~ 180 N mm ⁻¹	Yagati et al. ⁴⁰⁾
	AA6082, 4	UHSS, 4	-	AA2319, AA5087	2 ~ 4 (AA2319), 6 ~ 18 (AA5087)	128 MPa (AA2319), 65 MPa (AA5087)	Chang et al. ⁴⁸⁾
	AA5052, 1	GI, 2	54.6 ~ 110.5	AA4043	1 ~ 10	162 MPa	Ma et al. ⁴⁹⁾
AC pulsed GMA	AA6021, 1.6	Uncoated steel, 1.4	-	AA4043	1.14 ~ 3.2	173 MPa	Park et al. ³⁶⁾
AC Double-pulsed GMA	AA5052, 1	GI, 1	111	Pure Al AA4043, AA4047, AA5356	1 ~ 7 (AA4043, AA4047), ~ 30 (pure Al, AA5356)	112 MPa (AA5356), 165 MPa (Pure Al), 201 MPa (AA4043, AA4047)	Su et al. ^{13,14)}
Double sided arc joining	AA5052, 3	Low carbon steel, 3	85.8	AA4043	2.03	148.1 MPa	Ye et al. ⁵¹⁾
CMT	AA6016, 1	GI, 1	-	AA1080	2.3	-	Agudo et al. ⁵⁾
	AA6061, 1	GI, 1	200	AA4043	3 ~ 5	200 MPa	Cao et al. ⁶⁾
	AA1060, 1	GI, 0.6	-	AA4043	4	83 MPa	Zhang et al. ⁴¹⁾
	Al alloy, 1	GI, 1	55 ~ 91	AA4043	7 ~ 40	96 MPa	Zhang et al. ^{42,43)}
	AA5052, 1	Al-coated and GI, 1.2	111	AA4043, AA4047, AA5183, AA5356	5 (Al-Si filler), 12 ~ 13 (Al-Mg filler)	75 ~ 188 MPa	Kang and Kim ⁴⁴⁾
	AA5754, 2	GI, 3	-	AA4043 AA4047, Al-Si3-Mn	-	188 MPa	Milani et al. ⁴⁷⁾
	AA6061, 2	DP800, 1.6	110 ~ 140	AA4043	1.23 ~ 3.02	440 N mm ⁻¹	Madhavan et al. ⁵⁰⁾
coldArc	AA5754 and AA5052, 1 ~ 1.5	GI and GA, 1 ~ 1.2	36 ~ 126	AA4043	0.8 ~ 4.5	210 MPa (GA), 73 MPa (GA)	Das et al. ^{7,45,46)}

UHSS - ultra-high strength steel

reported to contain the phase layer thickness within 4 ~ 8 μm and resulted joint strength around 96 ~ 200 MPa in GMA^{15,41,42,49)}, laser beam¹⁸⁾ and laser-arc hybrid¹¹⁾ joining of aluminium and steel with Al-Si^{11,15,41,42)} and Zn-Al¹⁸⁾ based filler wires. In contrast, typical phase layer thickness of 2 ~ 7 μm and corresponding joint strength around 200 MPa were reported for a heat input range of 111 ~ 150 J mm⁻¹ in GMA,^{13,14,44)} and laser beam^{10,20)} joining of aluminium and steel with pure Al¹³⁾,

and Al-Si^{10,13,14,20,44)} based filler wires. Even a higher heat input range of 170 ~ 330 J mm⁻¹ resulted in typical phase layer thickness around 0.9 ~ 7 μm and joint strength around 80 ~ 200 MPa in GMA^{6,12)} and laser beam³¹⁾ based joining of aluminium and steel with Al-Si^{6,12,31)} based filler wires. In contrast, a lower heat input range of 56 ~ 156 J mm⁻¹ was found to result in the formation of thick layer of 12 ~ 20 μm and joint strength of 200 MPa in laser beam^{18,20)} and laser-arc hy-

Table 3 Filler wire composition on intermetallic phase layer thickness and the final joint strength for laser beam and GMA based joining processes

Filler wire	d_p (μm)	Strength	Process	Reference
Pure Al	2.3	-	CMT	Agudo et al. ⁵⁾
	2 ~ 7	165 MPa	AC double pulsed GMA	Su et al. ^{13,14)}
AA4043	3 ~ 5	200 MPa	CMT	Cao et al. ⁶⁾
	0.8 ~ 4.5	210 MPa	coldArc	Das et al. ⁷⁾
	4 ~ 7	188 MPa	AC double pulsed GMA	Su et al. ^{13,14)}
	5 ~ 15	194 MPa	Pulsed GMA	Zhang and Liu ¹⁵⁾
	1.14 ~ 3.2	173 MPa	Pulsed GMA	Park et al. ³⁶⁾
	-	199 MPa	Pulsed GMA	Shi et al. ^{37,38)} , Shao et al. ³⁹⁾
	4	83 MPa	CMT	Zhang et al. ⁴¹⁾
	7 ~ 20	96 MPa	CMT	Zhang et al. ^{42,43)}
	1 ~ 10	162 MPa	CMT	Ma et al. ⁴⁹⁾
	2.03	148 MPa	Double side arc joining	Ye et al. ⁵¹⁾
	1.5 ~ 13	162 MPa	Laser	Zhang et al. ²⁰⁾
	1.8 ~ 6.2	174.6 4 MPa	Laser	Sun et al. ²⁵⁾
AA4047	0.9 ~ 2.5	80 MPa	Pulsed GMA	Murakami et al. ¹²⁾
	1 ~ 4	201 MPa	AC double pulsed GMA	Su et al. ^{13,14)}
	5	175 N mm ⁻¹	CMT	Kang and Kim ⁴⁴⁾
	2	190 MPa	Laser	Sierra et al. ¹⁰⁾
	2 ~ 3	180 N mm ⁻¹	Laser	Saida et al. ²³⁾
	4 ~ 12	180 MPa	Laser - GMA hybrid	Thomy et al. ¹¹⁾
	3 ~ 6.5	130 MPa	Laser - GMA hybrid	Gao et al. ²⁷⁾
Zn-30%Al and Zn-15%Al	5	193 ~ 230 N mm ⁻¹	Laser	Mathieu et al. ¹⁷⁾
	8 ~ 12	200 MPa	Laser	Dharmendra et al. ¹⁸⁾
	10	190 MPa	Laser	Shabadi et al. ¹⁹⁾
AA5183 and AA5356	~ 30	112 MPa	AC double pulsed GMA	Su et al. ^{13,14)}
	12 ~ 13	188 MPa	CMT	Kang and Kim ⁴⁴⁾

brid¹¹⁾ joining of aluminium and steel with Al-Si^{11,20)} and Zn-Al¹⁸⁾ based filler wires.

6. Influence of Filler Wires on Intermetallic Phase Layer Thickness and Joint Strength

In general, pure-Al, Al-Si, Zn-Al and Al-Mg based filler wires were employed to join aluminium and steel sheets by GMA, laser beam and laser-arc hybrid processes. The pure-Al based filler wires typically resulted in phase layer thickness in the range of 2.3 ~ 7 μm and joint strength around 165 MPa in GMA^{5,14)} based joining techniques. The AA4043 filler wire formed layer thickness in the range of 1 ~ 20 μm and corresponding joint strength around 83 ~ 200 MPa in GMA^{6,7,13-15,36-39, 41-43,49,51)} and laser beam^{20,25)} based joining processes. In contrast, AA4047 filler wire resulted in phase layer thickness in the range of 0.9 ~ 12 μm and joint strength around 80 ~ 200 MPa in GMA^{12-14,44)}, laser beam^{10,23)} and laser-arc hybrid^{11,27)} processes.

The Zn-Al based filler wires, resulted the phase layer thickness in the range of 5 ~ 12 μm and joint strength around 200 MPa in laser beam¹⁷⁻¹⁹⁾ joining process. In contrast, AA5183 and AA5356 filler wires reported the growth of layer thickness around 7 ~ 13 μm and the joint strength of 112 ~ 188 MPa in GMA^{13,14,44)} based processes. Influence of filler wire composition on intermetallic phase layer thickness and the final joint strength for laser beam and GMA based joining processes is presented in tabular form as Table 3.

7. Conclusion

A brief survey of the experimental studies on joining of aluminium and steel sheets using laser beam, laser - arc hybrid and GMA based techniques is presented in the above sections. The effect of joining processes such as heat input and filler wire composition on the joint strength and formation of intermetallic phase layer at the joint interface are analyzed in details. The experimental

studies reported in the literature have shown that the heat input and filler wire composition would primarily influence the growth of phase layer at the joint interface and the final joint strength, irrespective of joining processes. However, the reported studies remained inconclusive about the permissible range of heat input to contain the phase layer thickness. Further, recent advancements in low energy pulsed current GMA techniques with controlled short-circuiting and metal transfer at low power have provided an opportunity to utilize these techniques for the joining of aluminium alloys and galvanized steels at a very low heat input.

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References

1. U. Diltthey and L. Stein, Multimaterial car body design: challenge for welding and joining, *Sci. Technol. Weld. Joi*, 11(2) (2006), 135-142
<https://doi.org/10.1179/174329306X85967>
2. J.E. Gould, Joining aluminum sheet in the automotive industry - a 30 year history, *Weld. J*, 91(1) (2012), 23s-34s
3. W.S. Miller, L. Zhuang, J. Bottema, A.J. Wittebrood, P.D. Smet, A. Haszler and A. Vieregge, Recent development in aluminium alloys for the automotive industry, *Mater. Sci. Eng. A*, 280(1) (2000), 37-49
[https://doi.org/10.1016/S0921-5093\(99\)00653-X](https://doi.org/10.1016/S0921-5093(99)00653-X)
4. H.K.D.H. Bhadeshia, Problems in the welding of automotive alloys, *Sci. Technol. Weld. Joi*, 20(6) (2015), 451-453
<https://doi.org/10.1179/15Z.000000000379>
5. L. Agudo, D. Eyidi, C.H. Schmaranzer, E. Arenholz, N. Jank, J. Bruckner and A.R. Pyzalla, Intermetallic Fe_xAl_y phases in a steel/Al-alloy fusion weld, *J. Mater. Sci*, 42(12) (2007), 4205-4214
<https://doi.org/10.1007/s10853-006-0644-0>
6. R. Cao, J.H. Sun, J.H. Chen and P. Wang, Cold metal transfer joining of aluminum alloys-to-galvanized mild steel, *J. Mater. Process. Tech*, 213(10) (2013), 1753-1763
<http://dx.doi.org/10.1016/j.jmatprotec.2013.04.004>
7. A. Das, M. Shome, S.F. Goecke and A. De, Joining of aluminium alloy and galvanized steel using a controlled gas metal arc process, *J. Manuf. Process*, 27 (2017), 179-187
<https://doi.org/10.1016/j.jmapro.2017.04.006>
8. X. Sun, E.V. Stephens, M.A. Khaleel, H. Shao, and M. Kimchi, Resistance spot welding of aluminum alloy to steel with transition material - from process to performance - part I: experimental study, *Weld. J*, 83(7) (2004), 188s-195s
9. T. Watanabe, H. Takayama and A. Yanagisawa, Joining of aluminum alloy to steel by friction stir welding, *J. Mater. Process. Tech*, 178(1-3) (2006), 342-349
<https://doi.org/10.1016/j.jmatprotec.2006.04.117>
10. G. Sierra, P. Peyre, F.D. Beaume, D. Stuart and G. Fras, Steel to aluminium braze welding by laser process with Al-12Si filler wire, *Sci. Technol. Weld. Joi*, 13(5) (2008), 430-437
<https://doi.org/10.1179/174329308X341852>
11. C. Thomy and F. Vollertsen, Laser-MIG hybrid welding of aluminium to steel - effect of process parameters on joint properties, *Weld. World*, 56(5-6) (2012), 124-132
<https://doi.org/10.1007/BF03321356>
12. T. Murakami, K. Nakata, H. Tong and M. Ushio, Dissimilar metal joining of aluminum to steel by MIG arc brazing using flux cored wire, *ISIJ Int*, 43(10) (2003), 1596-1602
13. Y. Su, X. Hua and Y. Wu, Effect of input current modes on intermetallic layer and mechanical property of aluminum-steel lap joint obtained by gas metal arc welding, *Mater. Sci. Eng. A*, 578 (2013), 340-345
<https://doi.org/10.1016/j.msea.2013.04.097>
14. Y. Su, X. Hua and Y. Wu, Influence in alloy elements on microstructure and mechanical property of aluminum-steel lap joint made by gas metal arc welding, *J. Mater. Process. Tech*, 214(4) (2014), 750-755
<https://doi.org/10.1016/j.jmatprotec.2013.11.022>
15. H. Zhang and J. Liu, Microstructure characteristics and mechanical property of aluminum alloy/stainless steel lap joints fabricated by MIG welding-brazing process, *Mater. Sci. Eng. A*, 528(19-20) (2011), 6179-6185
<https://doi.org/10.1016/j.msea.2011.04.039>
16. I. Lum, S. Fukumoto, E. Biro, D.R. Boomer, and Y. Zhou, Electrode pitting in resistance spot welding of aluminum alloy 5182, *Metall. Mater. Trans. A*, 35(1) (2004), 217-226
<https://doi.org/10.1007/s11661-004-0122-8>
17. A. Mathieu, R. Shabadi, A. Deschamps, M. Suery, S. Mattei, D. Grevey and E. Cicala, Dissimilar material joining using laser (aluminum to steel using zinc-based filler wire), *Opt. Laser Technol*, 39(3) (2007), 652-661
<https://doi.org/10.1016/j.optlastec.2005.08.014>
18. C. Dharmendra, K.P. Rao, J. Wilden and S. Reich, Study on laser welding-brazing of zinc coated steel to aluminum alloy with a zinc based filler, *Mater. Sci. Eng. A*, 528(3) (2011), 1497-1503
<https://doi.org/10.1016/j.msea.2010.10.050>
19. M. Shabadi, A. Suery and A. Deschamps, Characterization of joints between aluminum and galvanized steel sheets, *Metall. Mater. Trans. A*, 44(6) (2013), 2672-2682

- <https://doi.org/10.1007/s11661-012-1605-7>
20. M.J. Zhang, G.Y. Chen, Y. Zhang and K.R. Wu, Research on microstructure and mechanical properties of laser keyhole welding-brazing of automotive galvanized steel to aluminum alloy, *Mater. Design*, 45 (2013), 24-30
<https://doi.org/10.1016/j.matdes.2012.09.023>
 21. G.L. Qin, Y.H. Su and S.H. Wang, Microstructures and properties of welded joint of aluminum alloy to galvanized steel by Nd:YAG laser + MIG arc hybrid brazing-fusion welding, *T. Nonferr. Metal Soc.*, 24(4) (2014), 989-995
[https://doi.org/10.1016/S1003-6326\(14\)63153-8](https://doi.org/10.1016/S1003-6326(14)63153-8)
 22. G. Qin, L. Zhen, Y. Su, B. Fu, X. Meng and S. Lin, Large spot laser assisted GMA brazing-fusion welding of aluminum alloy to galvanized steel, *J. Mater. Process. Tech.*, 214(11) (2014), 2684-2692
<https://doi.org/10.1016/j.jmatprotec.2014.06.011>
 23. K. Saida, H. Ohnishi and K. Nishimoto, Fluxless laser brazing of aluminium alloy to galvanized steel using a tandem beam - dissimilar laser brazing of aluminium alloy and steels, *Weld. Int.*, 24(3) (2010), 161-168
<https://doi.org/10.1080/09507110902843065>
 24. J. Yang, Y. Li, H. Zhang, W. Guo, D. Weckman and N. Zhou, Dissimilar laser welding/brazing of 5754 aluminum alloy to DP 980 steel: mechanical properties and interfacial microstructure, *Metall. Mater. Trans. A*, 46(11) (2015), 5149-5157
<https://doi.org/10.1007/s11661-015-3079-x>
 25. J. Sun, J. Huang, Q. Yan, and Z. Li, Fiber laser butt joining of aluminum to steel using welding - brazing method, *Int. J. Adv. Manuf. Tech.*, 85(9-12) (2015), 2639-2650
<https://doi.org/10.1007/s00170-015-8137-4>
 26. J. Sun, Q. Yan, W. Gao and J. Huang, Investigation of laser welding on butt joints of Al/steel dissimilar materials, *Mater. Design*, 83 (2015), 120-128
<https://doi.org/10.1016/j.matdes.2015.05.069>
 27. M. Gao, C. Chen, S. Mei, L. Wang and X. Zeng, Parameter optimization and mechanism of laser - arc hybrid welding of dissimilar Al alloy and stainless steel, *Int. J. Adv. Manuf. Tech.*, 74(1-4) (2014), 199-208
<https://doi.org/10.1007/s00170-014-5996-z>
 28. S. Yan, Z. Hong, T. Watanabe and T. Jingguo, CW/PW dual-beam YAG laser welding of steel/aluminum alloy sheet, *Opt. Laser. Eng.*, 48(7-8) (2010), 732-736
<https://doi.org/10.1016/j.optlaseng.2010.03.015>
 29. S. Frank, Flux-free laser joining of aluminum and galvanized steel, *J. Mater. Process. Tech.*, 222 (2015), 365-372
<https://doi.org/10.1016/j.jmatprotec.2015.03.032>
 30. J. Ma, M. Harooni, B. Carlson and R. Kovacevic, Dissimilar joining of galvanized high-strength steel to aluminum alloy in a zero-gap lap joint configuration by two-pass laser welding, *Mater. Design*, 58 (2014), 390-401
<https://doi.org/10.1016/j.matdes.2014.01.046>
 31. M. Windmann, A. Rottger, H. Kugler, W. Theisen and F. Vollertsen, Laser beam welding of aluminum to Al-base coated high-strength steel 22MnB5, *J. Mater. Process. Tech.*, 217 (2015), 88-95
<https://doi.org/10.1016/j.jmatprotec.2014.10.026>
 32. R. Borrisutthekul, T. Yachi, Y. Miyashita and Y. Mutoh, Suppression of intermetallic reaction layer formation by controlling heat flow in dissimilar joining of steel and aluminium alloy, *Mater. Sci. Eng. A*, 467(1-2) (2007), 108-113
<https://doi.org/10.1016/j.msea.2007.03.049>
 33. G. Pardal, S. Meco, S. Ganguly, S. Williams and P. Prangnell, Dissimilar metal laser spot joining of steel to aluminium in conduction mode, *Int. J. Adv. Manuf. Tech.*, 73(1-4) (2014), 365-373
<https://doi.org/10.1007/s00170-014-5802-y>
 34. J. Huang, J. He, X. Yu, C. Li, D. Fan, The study of mechanical strength for fusion-brazed butt joint between aluminum alloy and galvanized steel by arc-assisted laser welding, *J. Manuf. Process.*, 25 (2017), 123-133.
<http://dx.doi.org/10.1016/j.jmapro.2016.11.014>
 35. L. Cui, B. Chen, L. Chen, D. He, Dual beam laser keyhole welding of steel/aluminum lapped joints, *J. Mater. Process. Tech.*, 256 (2018), 87-97
 36. H.J. Park, S., Rhee, M.J. Kang and D.C. Kim, Joining of steel to aluminum alloy by AC pulse MIG welding, *Mater. Trans.*, 50(9) (2009), 2314-2317
<http://dx.doi.org/10.2320/matertrans.M2009105>
 37. Y. Shi, L. Shao, J. Huang and Y. Gu, Effects of Si and Mg elements on the microstructure of aluminum - steel joints produced by pulsed DE-GMA welding / brazing, *Mater. Sci. Tech.*, 29(9) (2013), 1188-1124
<https://doi.org/10.1179/1743284713Y.00000000291>
 38. Y. Shi, G. Zhang, Y. Huang, L. Lu, J. Hunag and Y. Shao, Pulsed double-electrode GMAW-brazing for joining of aluminum to steel, *Weld. J.*, 93(6) (2014), 216s-224s
 39. L. Shao, Y. Shi, J.K. Huang and S.J. Wu, Effect of joining parameters on microstructure of dissimilar metal joints between aluminum and galvanized steel, *Mater. Design*, 66(B) (2015), 453-458
<https://doi.org/10.1016/j.matdes.2014.06.026>
 40. K.P. Yagati, R.N. Bathe, K.V. Raajulapati, K.B.S. Rao and G. Padmanabham, Fluxless arc weld-brazing of aluminium alloy to steel, *J. Mater. Process. Tech.*, 214(12) (2014), 2949-2959
<https://doi.org/10.1016/j.jmatprotec.2014.06.017>
 41. H.T. Zhang, J.C. Feng, P. He, B.B. Zhang, J.M. Chen and L. Wang, The arc characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminium to zinc-coated steel, *Mater. Sci. Eng. A*, 499 (1-2) (2009), 111-113
<https://doi.org/10.1016/j.msea.2007.11.124>
 42. H.T. Zhang, J.C. Feng, P. He and H. Hackl, Interfacial

- microstructure and mechanical properties of aluminium-zinc-coated steel joints made by a modified metal inert gas welding-brazing process, *Mater. Charact.*, 58 (2007) 588-592
<https://doi.org/10.1016/j.matchar.2006.07.008>
43. H.T. Zhang, J.C. Feng and P. He, Interfacial phenomena of cold metal transfer (CMT) welding of zinc coated steel and wrought aluminium, *Mater. Sci. Tech.*, 24(11) (2008) 1346-1349
<https://doi.org/10.1179/174328407X213152>
 44. M. Kang and C. Kim, Joining Al 5052 alloy to aluminumized steel sheet using cold metal transfer process, *Mater. Design*, 81 (2015), 95-103
<https://doi.org/10.1016/j.matdes.2015.05.035>
 45. A. Das, M. Shome, C.R. Das, S.F. Goecke and A. De, Joining of galvanized steel and aluminium alloy using controlled short circuiting gas metal arc welding process, *Sci. Technol. Weld. Joi.*, 20(5) (2015), 402-408
<https://doi.org/10.1179/1362171815Y.0000000032>
 46. A. Das, M. Shome, S.F. Goecke and A. De, Numerical modelling of gas metal arc joining of aluminium alloy and galvanized steels in lap joint configuration, *Sci. Technol. Weld. Joi.*, 21(4) (2016), 303-309
<https://doi.org/10.1080/13621718.2015.1104206>
 47. A.M. Milani, M. Paider, A. Khodabandeh and S. Nategh, Influence of filler wire and wire feed speed on metallurgical and mechanical properties of MIG welding - brazing of automotive galvanized steel/5754 aluminum alloy in a lap joint configuration, *Int. J. Adv. Manuf. Tech.*, 82(9-12) (2016), 1495-1506
<https://doi.org/10.1007/s00170-015-7505-4>
 48. Q. Chang, D. Sun, X. Gu, H. Li, Microstructures and mechanical properties of metal inert-gas arc welded joints of aluminum alloy and ultrahigh strength steel using Al - Mg and Al - Cu fillers, *J. Mater. Res.*, 32(3) (2017), 1-11
<https://doi.org/10.1557/jmr.2016.487>
 49. H. Ma, G. Qin, X. Bai, L. Wang, Z. Liang, Effect of initial temperature on joint of aluminum alloy to galvanized steel welded by MIG arc brazing-fusion welding process, *Int. J. Adv. Manuf. Tech.*, 86(9-12) (2016), 3135-3143
<https://doi.org/10.1007/s00170-016-8425-7>
 50. S. Madhavan, M. Kamaraj, L. Vijayaraghavan, K.S. Rao, Microstructure and mechanical properties of aluminium/steel dissimilar weldments: effect of heat input, *Mater. Sci. Tech.*, 33(2) (2017), 200-209
<https://doi.org/10.1080/02670836.2016.1176716>
 51. Z. Ye, J. Huang, W. Gao, Y. Zhang, Z. Cheng, S. Chen, J. Yang, Microstructure and mechanical properties of 5052 aluminum alloy/mild steel butt joint achieved by MIG-TIG double-sided arc welding-brazing, *Mater. Design*, 123 (2017), 69-79
<https://doi.org/10.1016/j.matdes.2017.03.039>
 52. Z. Ye, J. Huang, Z. Cheng, L. Xie, Y. Zhang, S. Chen, J. Yang, Study on butt joining 5052 aluminum alloy/Q235 mild steel by MIG-TIG double-sided arc welding-brazing process, *Weld. World*, 62(1) (2018), 145-154
<https://doi.org/10.1007/s40194-017-0516-z>