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Joining of aluminium alloy and galvanized steel using a controlled gas metal arc process

A. Das [a], M. Shome [b], Sven-F. Goecke [c], A. De [a,*]

[a] Indian Institute of Technology Bombay, Mumbai, India
[b] Tata Steel Limited, Jamshedpur, India
[c] Technical University of Applied Science, Brandenburg, Germany

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ABSTRACT

A precise control of the heat input is needed to restrict the development of Fe-Al brittle intermetallic compounds along the joint interface and the growth of the interface layer in mixed-material joints of aluminium and galvanized steel sheets. A novel study is presented here on the joining of aluminium alloys and galvanized steel sheets using a gas metal arc process with short-circuiting metal transfer and fast responsive control of current and voltage pulses. The influence of the processing conditions on the heat input, phase layer thickness, type of intermetallic compounds and joint strength is studied extensively. The permissible heat input is found to be in the range of 36–106 J mm^{-1} that has led to 0.68–6.10 μm thick phase layers along the joint interface with the maximum joint strength of 208 MPa.

1. Introduction

Joining of steel and aluminium alloys remains ever challenging due to their widely different thermophysical properties such as melting temperature and thermal conductivity [1,2]. The poor solubility of iron in aluminium also results in the formation and growth of Fe-Al brittle intermetallic compounds (IMC) such as Fe_2Al_5 and $FeAl_3$ along the joint interface [3]. Recent studies have showed that the thickness of the Fe-Al intermetallic phase layer can be restricted by a careful control of the heat input [4]. Several processes such as laser beam [5] and laser-arc hybrid [4] joining, gas tungsten arc [6] and gas metal arc [7] based techniques and friction stir welding [8] are examined for joining of aluminium and steel sheets. Joining processes based on pulsed current gas metal arc (GMA) are found fairly superior as they have provided fast responsive control of current pulses, metal transfer and heat input and easy adaptability to complex joint geometries and automation [7,9]. The purpose of the present study is therefore a systematic investigation to examine the suitability of an advanced pulsed current GMA process for the joining of hot-dip galvanized steel and automotive aluminium alloy sheets.

The reported studies on joining of aluminium alloys to steel sheets using GMA processes have shown a wide range of heat input to restrict the growth of the interface with Fe-Al intermetallic phases and improve the joint strength. For example, Zhang et al. [10,11] have used a heat input range of 55–91 J mm^{-1} to join aluminium alloy and hot-dip galvanized (GI) steel sheets, both of 1 mm in thickness, by AA4043 (Al-5%Si) filler wire. They have found the intermetallic phase layer thicknesses around 7–40 μm with the maximum joint strength of 96 MPa. In contrast, Zhang and Liu [12] have joined similar alloy combinations and achieved the maximum joint strength of 194 MPa using heat inputs in the range of 63–99 J mm^{-1}. These authors have reported the maximum intermetallic phase layer thickness of 10 μm [12]. Likewise, Su et al. [13] have reported the maximum joint strength of 200 MPa at a moderate heat input of 111 J mm^{-1} and a permissible range of phase layer thicknesses from 1 to 7 μm. Kang and Kim [14] have observed a similar phase layer thickness of 5 μm for a heat input of 112 J mm^{-1} in joining of aluminium alloy and GI steel sheets in the thickness ranges of 1–2 mm using Al-Si based filler wire. Yagati et al. [9] have obtained the best joint strength for a heat input of 62.75 J mm^{-1} in joints of 2 mm thick AA6061 and 1.2 mm thick GI steel sheets. These authors have reported the phase layer thicknesses in the range of 1.5–4.0 μm [9]. In joining of 1.5 mm AA5052 and 1.2 mm galvannealed (GA) steel sheets, Das et al. [7,15] have reported the highest joint strength of 73 MPa with a heat input range of 84–126 J mm^{-1}. The phase layer thicknesses are restricted within 1.3–2.0 μm [7]. Using a higher heat input range of 170–255 J mm^{-1} for joining of

* Corresponding author.
E-mail addresses: atd.kgec@gmail.com (A. Das), mshome@tatasteel.com (M. Shome), goecke@th-brandenburg.de (S.-F. Goecke), amit@iitb.ac.in (A. De).

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thicker aluminium and steel sheets up to 2 mm, Murakami et al. [16] have attained the joint strength of 80 MPa and the phase layer thicknesses in the range of 0.9–2.5 μm. Cao et al. [2] have used a typical heat input of 200 J mm−1 for joining of thinner sheets of aluminium alloy and GI steel, and reported the phase layer thicknesses around 3–5 μm with the maximum joint strength of 200 MPa. These studies show the use of a wide range of heat inputs in thermal joining of aluminium alloys and galvanized steel sheets. However, the influence of heat input on joint strength and intermetallic phase layer thickness has remained inconclusive.

Aluminium and galvanized steel sheets are also joined using laser beam and laser-arc hybrid joining techniques without any remarkable improvement of the joint properties. For example, Thomy and Vollertsen [4] have employed a heat input range of 47–56 J mm−1 to join 1.15 mm thick AA6016 and 1 mm thick GI steel sheets with AA4047 (Al-12%Si) filler wire. These authors have reported intermetallic phase layer thicknesses from 4 to 12 μm with the maximum joint strength of 184 MPa [4]. Sierra et al. [5] have used higher heat inputs of 120–150 J mm−1 to join similar sheet combinations of 1.0–1.2 mm thickness and reported the phase layer thickness of 2 μm and the maximum strength of around 180 MPa. Windmann et al. [17] have used another Al-Si3-Mn filler wire and higher heat input ranges of 240–300 J mm−1 and, achieved the phase layer thicknesses in the range of 2–7 μm with the maximum joint strength of 175 MPa. In another study, Bergmann et al. [18] have joined aluminium and steel sheets with aluminized coating and reported an intermetallic phase layer thickness around 16–34 μm with the maximum joint strength of 135 MPa.

The influence of heat input on the types of intermetallic compounds (IMC) in joining of aluminium alloys and galvanized sheets is also examined. Zhang et al. [10,11] and Su et al. [13] have reported the formation of brittle IMCs e.g. Fe_2Al_5 and $FeAl_3$ (or, Fe_4Al_{13}) for a heat input range of 55–111 J mm−1. Das et al. [7] have observed similar IMCs in joints of aluminium alloys and GA steel sheets. Higher heat inputs of 170–250 J mm−1 have led to the formation of Al-Si-Fe based IMC e.g. $Fe_2Al_{7.4}Si$ [16]. In contrast, Zhang and Liu [12] have reported the formation of a ternary IMC e.g. $FeAl_{4.5}Si$ at a lower heat input range of 63–99 J mm−1. With laser assisted joining techniques, a heat input range of 47–56 J mm−1 has resulted in the formation of Fe_2Al_5 along the joint interface [4]. Sierra et al. [5] have considered a higher heat input range of 120–150 J mm−1 and reported the formation of a ternary IMC phase e.g. $Fe_2Al_{7.4}Si$. In contrast to the commonly used Al-Si based filler wire, use of a Al-Si3-Mn filler wire and a higher heat input range of 240–330 J mm−1 have led to the formation of Fe_2Al_8Si and $FeAl_3$ phases [17].

In summary, the reported experimental studies have provided an understanding of the critical issues in joining of aluminium alloy and zinc-coated steel sheets using either GMA or laser-assisted hybrid arc techniques. The formation of a continuous phase layer along the joint interface in thermal joining of mixed materials such as aluminium and steel has been investigated by several authors [2–5,10,16,17]. The Fe-Al intermetallic compounds, Fe_xAl_y, that are commonly evolved in the phase layer are found to be brittle in nature and their brittleness increases significantly with increasing concentration of aluminium [3,4,6,13]. As a result, the key aim in all joining processes is to minimize or impede the evolution and growth of especially the brittle Fe_xAl_y compounds by controlling the heat input [2,4,7,10,16]. The ability of the advanced pulsed current GMA techniques to contain the heat input, the resulting Fe-Al intermetallic phase layer thickness at the joint interface and the formation of IMCs are not examined systematically and exhaustively. We present here an experimental study on joining of AA5754 alloy and hot-dip galvanized (GI) steel sheets using an advanced pulsed current GMA process with short-circuiting metal transfer. The primary emphasis is a quantitative understanding of the real-time current and voltage transients and consequent heat input during the joining process. The joint bead profiles, intermetallic phase layer thickness and types of IMCs, and joint strength are examined and correlated with the processing conditions and the heat input.

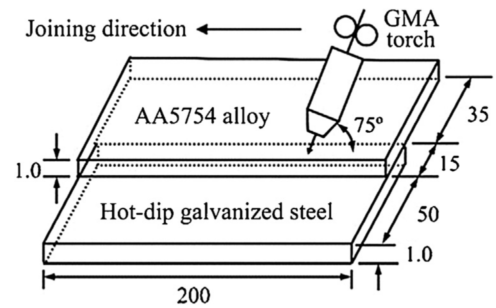

Fig. 1. Schematic diagram of experimental set-up for joining of AA5754 and GI steel sheet using gas metal arc process.

2. Experimental investigation

AA5754 aluminium alloy and hot-dip galvanized (GI) steel sheets are joined using a AA4043 filler wire in lap joint configuration (Fig. 1). The thicknesses of both the steel and aluminium sheets, and the filler wire diameter are 1.0 mm. A typical GMA welding power source (EWM alpha Q551) is employed to join the sample sheets using short-circuiting metal transfer that has provided fast responsive control of current and voltage pulses. Table 1 shows the chemical composition and ultimate tensile strength (UTS) of the sheets and the filler wire. Pure argon (99.999%) at a flow rate of 15 l min−1 is used as the shielding gas. The joining is done in back-hand mode with the GMA torch directed on the edge of aluminium alloy and leaned at an angle of 75° with the horizontal. The current and voltage waveforms are monitored using a pc interfaced data acquisition system (Graphtec make GL 900-4) at concurrent sampling rates of 100 kHz. The time-averaged current (I_A), arc power (P_A) and the pulse frequency (f) are estimated as [7]

$$I_A = \frac{\sum_{n=0}^{\tau} I_n t_n}{\sum_{n=0}^{\tau} t_n}, \quad (1)$$

$$P_A = \frac{\sum_{n=0}^{\tau} I_n V_n t_n}{\sum_{n=0}^{\tau} t_n}, \quad (2)$$

$$f = \frac{1}{\sum_{n=0}^{\tau_1} t_n}, \quad (3)$$

where I_n, V_n and t_n refer respectively to the instantaneous values of current, voltage and time, τ refers to either a short-circuiting or arcing period, and τ_1 is total time duration of short-circuiting and arcing periods for a complete current cycle. The variability in the estimated values of time-averaged current (I_A), arc power (P_A) and pulse frequency (f) is examined over 20 cycles in each case. The duration of the short-circuiting and arcing periods are examined from the current and voltage gradients in the corresponding transient records for a process condition. The beginning of the short-circuiting period is considered from the instant of sharp drop