Materials and Design 54 (2014) 184–195

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Study of metallurgic and mechanical properties of laser welded heterogeneous joints between DP600 galvanised steel and aluminium 6082

A. Kouadri-David *, PSM Team

European University of Brittany, France, INSA, LGCGM, EA 3913, 20 Avenue des Buttes des Coesmes, F-35708 Rennes, France

ARTICLE INFO

Article history:
Received 7 April 2013
Accepted 28 July 2013
Available online 6 August 2013

Keywords:
Laser lap welding
Microstructure
Shearing strength
Steels
Aluminium

ABSTRACT

This investigation focuses on the feasibility of heterogeneous welded joints between DP600 steel and aluminium 6082. The process adopted used a power laser in two modes: keyhole welding and laser-induced reactive wetting. All the results of the study show that the use of laser welding of galvanised sheets, in the keyhole mode, can achieve a joint shear strength of 140 MPa by optimising the process parameters and controlling the penetration, which must be limited to 600 μm. Another key factor with this welding method is control of the inter-sheet gap, which was achieved by using a clamping system that ensured a rigid joint while maintaining a constant gap sufficient to allow the escape of zinc vapour. This approach enabled an increase in shear strengths of 200 MPa to be obtained and the zinc acted as a beneficial factor to the welding process. With the laser-induced reactive wetting mode, the joint between galvanised sheets was more brittle because of the formation of a non-uniform reaction layer. With this mode, the presence of zinc is a factor that limits the growth of the reaction layer and, at the same time, leads to a mechanical deterioration of the joint; test results indicate that mechanical strength was limited to about 80 MPa.

1. Introduction

When considering the associated economics of energy in the transport industry the increase in weight currently presents an important challenge. The most obvious solution is to use the best materials in a coherent fashion that will guarantee the quality of the product with regard to its use and the associated constraints with respect to weight gain. Within this context, the design of a vehicle involves a large number of materials, each fulfilling a precise role. The low density of aluminium, in these circumstances, presents an efficient solution by replacing steel components with aluminium. However steel is necessary for the construction of structural components, thus the ideal solution is to combine the two materials. To ensure integrity of a composite structure, which is an attractive solution, the solution to the key problem of welding the two dissimilar materials must be addressed. This solution depends on the welding mode and the difficulty of welding two materials with differing mechanical and metallurgical properties.

Conventional welding processes involve total fusion (Arc, MIG/TIG) and do not allow the welding of two dissimilar metals because of the metallurgical incompatibility, for example aluminium and steel. The main problem is due to the large difference in melting temperatures of aluminium alloys ($T_m = 660\,°C$) and steels ($T_m = 1536\,°C$). During the passage into a liquid state, the poor metallurgical compatibility between the two materials presents a number of problems. There is virtually no miscibility between Fe and Al and brittle inter-metallic phases form such as Fe_2Al_5 or $FeAl_3$ [1–4] at the joint interface, leading to a diminution of the mechanical properties of the welded joint [2,3]. One solution is braze-welding, which does not involve melting of the base materials and thus avoids the problems linked to incompatibility. Workable solutions to produce this type of joint have been developed [5–7]. Braze welding with Al–12 filler wire enables welds to be formed with good mechanical properties [8]. Using the same technique with Zn–Al filler wire, Mathieu et al. [9] and Laukant et al. [10] showed that galvanised steel to aluminium joints could be formed without the use of flux which is necessary for reactive wetting of non-galvanised steel. The growth of these intermetallic phases depends on the composition of the filler wire and the anisothermal kinetics created during the brazing process at the interface steel/weld bead. Numerous publications deal with these intermetallic phases occurring during welding steel/aluminium [11–13]. Published results show that the welds have interfacial resistance for phase thicknesses below about 10 μm. However, if the growth of these brittle phases is not controlled, the welds produced often exhibit a mechanical strength diminution due to the formation of a layer of brittle phases at the steel/weld bead interface [1–4].

---

* Tel.: +33 (0)2 23 23 86 14.
E-mail address: afia.kouadri-henni@insa-rennes.fr

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.07.093

Another problem in the development and sustainability of a steel/aluminium joint comes from poor wetting of molten aluminium on steel. Most of the authors, cited above, use a flow reducer to allow steel wetting. However, brazing is one possible solution; this requires specific techniques and certain restrictions (use of chemical flux, brazing in vacuum or inert gas atmosphere, surface preparation, etc.) to allow wetting of the filler metal on the base metal. Moreover, the disadvantages are the additional costs generated by the flux application and the subsequent cleaning necessary to remove all residues detrimental to corrosion resistance. Subsequently new solid phase or paste welding techniques were developed, such as friction stir welding [14–16], or explosion welding [17,18], that enable this type of weld; however they involve some complexity and implementation cost. These techniques have been applied with success to the welding of steel and aluminium. Finally, the use of the laser process shows that it could lead to the best compromise and a good alternative solution for welding aluminium and steel plate. Laser processes are now widely used in the automotive industry for homogeneous assembling due to ease of access, positioning of the laser heads and high welding speeds. Moreover, over the past ten years many studies have been conducted on laser steel/aluminium welding in the vapour capillary mode [19,20], by laser-induced reactive wetting [4], and by braze-welding with Zn–Al or Al–Si filler wire [8–10], to obtain good mechanical properties in static tensile stress curve. For example, in a study of laser welding in lap joint configuration of low-carbon steel alloy 5052, Katayama et al. [21] showed that the depth of penetration of steel in aluminium was the key factor. For penetrations greater than 0.4 mm, the mechanical behaviour of the weld decreases significantly due to the large quantity of intermetallic phases leading to the appearance of cracks in the weld. Kreimeyer et al. [8] obtained good strength results (180 MPa) for welds of galvanised or non-galvanised steel through the interaction between solid steel and liquid aluminium with the use of a clamping system that ensured a pressure at the inter-sheet interface. These results were confirmed by Rathod and Kutsuna [22] and by Sierra et al. [23], by inducing the melting of aluminium by laser heating of steel, as originally envisaged by Kreimeyer et al. [8]. However, Kutsuna and Rathod assert that maximum mechanical strength is obtained by limiting the thickness of the intermetallic phases to below 10 μm. Conversely, Miyashita et al. [7] observed the increase in the weld strength with the increase in the width of the reaction layer, which is necessarily accompanied by an increase in thickness. The cost of laser processes, although its use is becoming more common, remains an obstacle to its widespread use. For this reason in recent years we have seen the use of arc welding MIG or MIG-Laser hybrid, resistance spot welding for weld-brazing steel/aluminium, which was initially carried out by laser process [24–26]. These studies have also shown the possibility of obtaining a good quality joint with the use of Al–Si filler wire and welding speeds equivalent to laser process.

The objective of this study is to investigate steel/aluminium welding and laser-induced wetting laser, with the aim of comparing the mechanical properties resulting from the different modes used; also to discuss the ease of implementation and the robustness of each mode. The studies reported in this paper are based on the use of galvanised steel; the zinc layer protects the steel from oxidation and provides a very good wetting of the seam on the steel sheet without using flux. This characteristic was used as a factor that acts as a flux and therefore promoting the bonding between the two chosen materials – DP600 steel galvanised and aluminium 6082. The techniques used involve the welding of steel and aluminium in a lap joint configuration. The laser weld was carried out in two modes: The “keyhole” mode which involves welding steel to aluminium but trying to limit penetration into aluminium. The second mode used was laser-induced reactive wetting in which the laser beam irradiates the surface of the steel without it melting and melting by conduction the underlying aluminium. A similar technique was used by Rathod and Kutsuna [22] to weld aluminium 5052 alloy and low carbon steel.

2. Materials and experimental techniques

2.1. Materials

The materials used in this study were a dual phase steel, type DP600, which is widely used in the automobile industry and the aluminium alloy 6082, which is equally widely used in the automobile and aeronautic industries. The chemical composition and mechanical properties are set out in Tables 1 and 2. The steel and aluminium alloy used were in the form of 1.2 mm thick sheets. The steel was galvanised, the thickness of the zinc coating being 10 μm.

2.2. Laser welding procedure

Welding of aluminium and steel sheets was carried out solely by laser. The configuration adopted was a lap joint as shown in Fig. 1. To optimise the welding of the aluminium and steel sheets two modes of laser weld were used; (1) keyhole (vapour capillary) and (2) conduction mode (reactive wetting).

2.2.1. Keyhole laser welding mode

Two configurations were used for lap joint welding in the vapour capillary (keyhole) mode:

(i) Steel sheet above aluminium.
(ii) Aluminium sheet above steel.

In the configuration where the steel was above the aluminium, the laser beam was focussed on the surface of the steel sheet thus generating the vapour capillary which traverses the steel and penetrates into the aluminium to create a heterogeneous bond. The two materials pass into a liquid phase at the wall of the vapour capillary (or keyhole). Sheets of steel and aluminium (300 mm long, 100 mm wide and 1.2 mm thick) were prepared by polishing with SiC 1200 abrasive paper (with the exception of the galvanised steel) and degreased with acetone. For this welding mode brazing flux was not used thus eliminating the formation of iron and aluminium oxides. All of the laser welding was carried out using a 4 kW Nd:YAG laser in a continuous wave mode (HL 4006 Trumpf). The power range was 1–3 kW and the welding speed ranged from 1 m/min to 3 m/min; the 200 mm focal length lens producing a spot diameter of 0.6 mm.

2.2.2. Conduction mode: laser-induced reactive wetting

Laser-induced reactive wetting welding in the lap joint configuration was carried out by the direct fusion of aluminium in a horizontal position to favour the flow of aluminium under the action of gravity. The tests were carried out using a Nd:YAG laser in the conduction mode, the power range was 1–1.5 kW and the weld speed ranged from 0.5 m/min to 1.5 m/min. A 200 mm focal length lens was used in a defocus mode, the focal point being situated beneath the work piece ($f = -20$ mm). The weld pool was protected from oxidation by a 10 l/min flow of argon gas.

2.3. Metallurgical analysis

After mechanical polishing to a mirror finish, the welds were examined by optical microscope. The microstructure of the steel was exposed by Nital Etchant (4% HNO_3, 96% C_2H_5OH) and that of aluminium by the reaction of Keller Etchant (2.5 ml of HNO_3,