Optics and Lasers in Engineering 67 (2015) 22–30

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Application of laser in seam welding of dissimilar steel to aluminium joints for thick structural components

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ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form
23 August 2014
Accepted 19 October 2014

Keywords:
Laser welding-brazing
Conduction
Intermetallic compound
Steel
Aluminium alloy

ABSTRACT

Laser welding-brazing technique, using a continuous wave (CW) fibre laser with 8000 W of maximum power, was applied in conduction mode to join 2 mm thick steel (XF350) to 6 mm thick aluminium (AA5083-H22), in a lap joint configuration with steel on the top. The steel surface was irradiated by the laser and the heat was conducted through the steel plate to the steel-aluminium interface, where the aluminium melts and wets the steel surface. The welded samples were defect free and the weld micrographs revealed presence of a brittle intermetallic compounds (IMC) layer resulting from reaction of Fe and Al atoms. Energy Dispersive Spectroscopy (EDS) analysis indicated the stoichiometry of the IMC as Fe_2Al_5 and $FeAl_3$, the former with maximum microhardness measured of 1145 HV 0.025/10. The IMC layer thickness varied between 4 to 21 μm depending upon the laser processing parameters. The IMC layer showed an exponential growth pattern with the applied specific point energy (E_{sp}) at a constant power density (*PD*). Higher *PD* values accelerate the IMC layer growth. The mechanical shear strength showed a narrow band of variation in all the samples (with the maximum value registered at 31.3 kN), with a marginal increase in the applied E_{sp}. This could be explained by the fact that increasing the E_{sp} results into an increase in the wetting and thereby the bonded area in the steel-aluminium interface.

1. Introduction

In recent past the surface transportation industry has been challenged to reduce fuel consumption and to comply with the governmental policies to lower the carbon emissions. To achieve these objectives, fuel efficient engines and mass efficient structural materials, aiming to reduce the total weight of the vehicle, are required. Therefore, light alloys are increasingly in use along with the traditional structural materials in vehicle designs. Aluminum (Al) is one of the materials of choice as it is cost effective, has high specific modulus and is corrosion resistant. The latest design solutions are aimed at using a higher proportion of Al as a structural material. Therefore, a cost effective and energy efficient joining solution with steel and Al would be vital to realize the potential of such innovative design solutions. The main issues associated with the joining of steel to Al are their different physical properties (e.g. melting temperatures, thermal expansion and conductivity), the nearly zero solid solubility of Al in iron (Fe) and zero solid solubility of Fe in Al and the resulting formation of intermetallic compounds (IMC). The diffusion of Fe and Al atoms at the Fe-Al interface forms different types of IMCs that are harmful for the structure due to their brittle behaviour. The most frequently reported IMCs are $FeAl_3$ and Fe_2Al_5.

Many studies have been carried out with the goal of understanding and minimizing the Fe-Al reaction. Some researchers were focused on the study of Fe-Al reaction between molten Al and solid steel, controlling the time-temperature and evaluating the IMC layer composition and growth [1–3], whilst others assessed the influence of other alloying elements on the IMC layer thickness growth [4,5]. The research developed by Shih et al. is an example of the latter point, where a steel bar was dipped in different molten Al alloys (pure, Si, Mg and Si-Mg based) during different time intervals, to evaluate the influence of these elements on the Fe-Al reaction [5]. The Al alloy containing Si and Mg showed the thinnest IMC layer.

The physical state of the alloys (solid or liquid) at the joint interface during the joining process is one of the determining factors for the formation of IMC because it directly controls the activity and mobility of the atoms of the participating alloys.

In solid state joining processes, such as friction stir welding [6] or linear friction welding [7], the formation of the Fe-Al IMC is usually minimized because there is basically only plastic deformation of the Al and the temperature generated during the joining process is very low (usually lower than the melting temperature of

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http://dx.doi.org/10.1016/j.optlaseng.2014.10.006
0143-8166/

the substrate). Explosion welding has another advantage, as the process happens so quickly there is almost no time for the reaction between Fe and Al and so the IMC layer is also very thin as demonstrated in [8–10].

Laser welding-brazing technique produces a joint between solid steel and molten Al [11–14] and is usually applied with filler wire. The interaction between both metals using this technique is minimal and consequently, sound dissimilar joints are produced with mechanical strength either identical or close to the weaker of the two metals (steel or Al plate, depending on the cross-sectional area of the specimen). An alternative technique was assessed in which a rolling system was combined to the laser [15–17]. The principle of this technique is to heat the substrate with the laser and immediately apply pressure on the soft metal with a roller to improve the contact in hot stage and thus the bonding. This way sound joints could be produced with IMC layer thickness less than 10 μm (many researchers have considered 10 μm as a reference maximum value of IMC layer thickness for an acceptable steel to Al joint [18]). Resistance spot welding applied to the steel to Al joining was also investigated [19–22]. Even though this process is a solid state pressure welding process, the researchers couldn't prevent formation of the IMCs and the samples failed from the interface when tested under tensile loading.

On the other hand, when both metals are in liquid state during the joining process, as is the case of the high power laser welding in keyhole mode [23–25], thick Fe-Al IMC layers are formed due to uncontrolled reaction and the joints are fragile.

It is well known from previous studies that the Fe-Al reaction depends on the welding temperature and time. IMC formation and growth is favoured when the welding thermal cycle is prolonged. This is expected because formation of IMC is a diffusion controlled process and prolonged time and higher temperature will allow more diffusion. Borrisutthekul et al. observed that under such conditions the IMC layer becomes thicker and as a result the joint mechanical strength would be lower [26].

So far in the area of joining this specific dissimilar combination, most of the research focus is towards the automotive industry and therefore, only thin (∼1 mm) sheets of steel and Al have been investigated. For maritime application, where thick (>3 mm) plates are used, only few papers were found, for instance the work produced by Thomy et al. using the laser-MIG hybrid process to join 3 mm plates of steel and Al in a butt joint configuration [27]. At present, in many industrial applications an explosion bonded hybrid transition bar, half Al and other half Fe, is used for successful joining of steel and Al (Fig. 1). However, the resulting

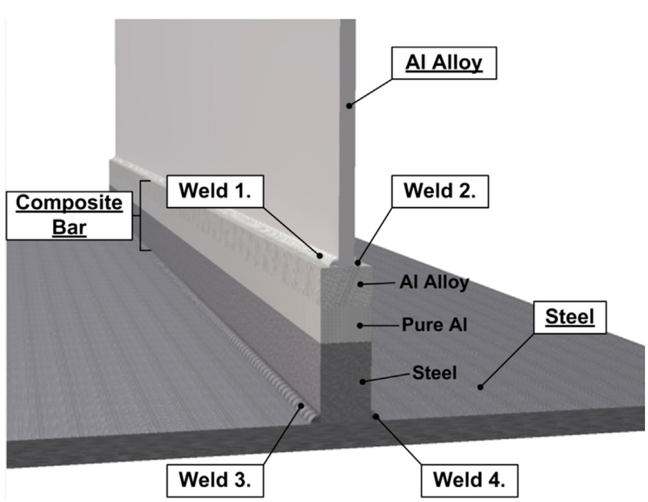

Fig. 1. Schematic representation of the dissimilar metal joint of steel to aluminium with the transition bar

joining process is not cost effective as it increases the cost of production through the cost of the bar and complicated logistics of operation. In addition, four fillet welds were necessary when a transition bar is used, instead of two, if Fe and Al were joined directly. The cost effectiveness and mass efficiency are thus reduced in such structures.

The overall aim of the present research programme is to develop a process in which thick plates of steel can be joined directly to Al without application of a filler material. Application of laser to join steel to aluminium in overlap configuration by welding-brazing process was investigated where the laser applied on the steel surface is conducted through and melts the aluminium to wet the steel surface. This minimizes random mixing of the two alloys as steel remains in solid state. However, in order to achieve viable joint it is necessary to understand the underpinning interaction between the laser source and the alloys and correlate the microstructural constituents of the interface with the interaction parameters and finally to the mechanical strength of the joint. This will enable development of a cost effective, design and energy efficient joining solution between Fe and Al with appropriate mechanical strength and metallurgical characteristics suitable for the intended application. In order to achieve this, an experimental matrix based on fundamental laser material interaction parameters was defined and the growth of Fe-Al IMC is correlated with the transient thermal (time-temperature) cycle resulting from the laser-material interaction.

2. System Parameters versus fundamental material interaction Parameters

In research and industrial application of laser welding, the vast majority of results is presented in terms of the laser system parameters, such as laser power (P), laser beam diameter (D_{beam}) and travel speed (TS). However, these parameters alone are not sufficient to describe the interaction of the laser beam with the material. Welding experiments using the fundamental material interaction parameters ($FMIP$), which include power density (PD), interaction time (t_i) and specific point energy (E_{sp}), have proven to be able to fully characterize the laser welding process [28].

As mentioned before, when a laser beam interacts with a material the total energy input cannot be controlled by individual control of either of these three parameters. Within the defined fundamental laser material interaction parameters, power density is defined as the ratio of the power to the applied area of the spot as shown in Eq. (1). This parameter is one of the chief determinant of welding mode (conduction and keyhole) [29]. Interaction time is defined by the ratio of laser travel speed to the spot size and signifies the irradiation time of an infinitesimal element within the laser spot. Calculation of interaction time (t_i) is shown in Eq. (2). The total laser energy delivered within a spot designated here as specific point energy is shown in Eq. (3) which is the product of power density, interaction time and the total area of the spot [30].

$$\text{Power density } [W.m^{-2}] = \frac{\text{Laser Power}}{\text{Area}_{beam}} \quad (1)$$

$$\text{Interaction time } [s] = \frac{\text{Diameter}_{beam}}{\text{Travel speed}} \quad (2)$$

$$\text{Specific point energy } [kJ] = \text{Power density} \times \text{Interaction time} \times \text{Area}_{beam} \quad (3)$$

Researchers investigated on FMIP emphasized that parameters developed in this process are transferrable between different laser systems [31] and shown direct correlation between FMIP, thermal profile and weld metal geometric profile.