Journal of Materials Processing Technology 222 (2015) 365–372

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Flux-free laser joining of aluminum and galvanized steel

Sascha Frank*

Fraunhofer Institute for Production Technology IPT, Steinbachstr. 17, 52074 Aachen, Germany

ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form 16 March 2015
Accepted 19 March 2015
Available online 30 March 2015

Keywords:
Joining
Laser brazing
Welding
Mixed-metal joint
Hybrid process

ABSTRACT

Joints between aluminum and galvanized steel pose a challenge for current manufacturing technologies. A hybrid joining method, which combines a pulsed and a continuous laser beam in a single process, has been identified as a potential solution for this challenge. The feasibility of this approach is verified by joining different base material alloys using zinc- and aluminum-based consumables. It is shown that the double beam method can be applied to different joint geometries by joining both double-flanged joints and lap joints. An analysis of the joint microstructure using metallographic cross-sections and transmission electron microscopy shows that intermetallic compounds can be limited to non-critical amounts. Tensile tests show that joint strengths in excess of 150 MPa can be achieved for both types of joint geometries. When shear loads are applied, the use of aluminum-based consumables leads to superior strength.

1. Introduction

Iron and aluminum possess a strong tendency to form intermetallic compounds (IMCs). These IMCs will form at the steel–aluminum interface during a thermal joining process. Since they are highly brittle, the formation of IMCs can lead to a drastic reduction of the joint strength. However, good mechanical properties can be attained when the thickness of the intermetallic layer is less than 10 μm. This was shown by Radscheit (1997) in investigations on joining galvanized steel and aluminum using a flux-based process. Laukant (2007) confirmed this result by performing a detailed microstructural and mechanical analysis on weld-brazed joints. Furthermore, it is possible to limit the growth of IMCs to non-critical values by minimizing the process temperature and process duration. This was shown by Mathieu et al. (2006), who used thermographic measurements and thermal simulation to correlate the development of the IMC layer to thermal effects.

Laser joining technologies are particularly well-suited for achieving the aforementioned goal. Lasers possess the ability to focus high energy densities on a small area. This makes it possible to combine short process times and high cooling rates by reaching high joining speeds. For this reason, several approaches to join galvanized steel and aluminum using laser technology have already been developed.

Many of these approaches require the use of chemical fluxing agents. These fluxes are used to destroy the thermally highly resistant oxide layer of the aluminum, making it possible to reduce the required energy input. For example, Thomy and Vollertsen (2009) have shown that it is possible to join galvanized steel and aluminum using a hybrid laser MIG process and AlSi12 filler wire. This process requires the use of chemical fluxes. On the aluminum side, a weld is formed by melting the aluminum sheet. The steel sheet is not molten and merely wet by the liquid aluminum, creating a mix between a brazed connection and a weld. By avoiding high temperatures near the interface to the steel sheet, the growth of IMCs is counteracted.

Similar weld-brazed joints were created by Engelbrecht et al. (2006) using a flux-cored zinc alloy wire and only a single continuous wave (cw) laser source. However, the use of fluxes also entails disadvantages like the challenge of reproducible flux application. According to Thomy and Vollertsen (2009), flux fumes can also cause the formation of pores. Additional work steps are commonly required for flux application and post-process cleaning. While flux-cored wires address some of these issues, they can cause problems with wire feed units due to their low stiffness, as reported by Laukant (2007). Depending on the type of chemical used, fluxes can also corrode the workpieces and be hazardous to health and environment. For these reasons, methods of joining aluminum and steel without relying on fluxes are also a matter of intense research.

Mathieu et al. (2007) report that it is possible to create weld-brazed lap joints without using fluxes when zinc-based consumables are used. However, the thickness of the intermetallic layer may exceed 10 μm and further optimization of the process

---

* Tel.: +49 241 8904 447.
E-mail address: sascha.frank@ipt.fraunhofer.de

http://dx.doi.org/10.1016/j.jmatprotec.2015.03.032

will require advanced measures for temperature control. According to Engelbrecht et al. (2006), avoiding the use of fluxes may also lead to insufficient wetting of the base materials. This problem was circumvented by Saida et al. (2010) by using an additional cw laser to preheat the steel sheet of the lap joint, thus improving the wetting and spreading of the melt by increasing the thermal energy input. In this process, the aluminum-based consumable AlSi12 was used. As shown by the cross-sections published by Saida et al. (2010), the joints created by this method were also of the weld-brazed type.

All of the methods discussed above benefit from the fact that the Zn coating of galvanized steel facilitates the wetting process. This was shown in detailed wetting experiments by Gatzen et al. (2014). However, Yagati et al. (2014) have recently reported that it is also possible to join aluminum and uncoated steel thermally by employing a pulsed MIG welding system to create weld-brazed lap joints. The use of fluxes was circumvented in this case by grinding, brushing and cleaning the aluminum material before the joining process in order to reduce the thickness of the oxide layer.

In summary, research has shown that it is possible to create sound joints between steel and aluminum by weld-brazing. However, it is currently only possible to reconcile conflicting demands such as low joining temperatures and good wetting behavior by using chemical fluxes. The approach presented in this paper strives to solve this dilemma by superimposing a pulsed (pw) and a continuous (cw) laser beam in a common process zone. As shown by Donst (2012), a pw laser can be used in such a process to destroy the aluminum's protective oxide layer through a combination of ablation and material vaporization. Due to short pulse durations and a comparatively low average power output, the influence of the pulsed laser on the thermal process field is small. This makes it possible to join aluminum materials without the aid of chemical fluxes while maintaining a comparatively low cw output power level.

The specific advantages of the double beam technology have led to the hypothesis that this method can be applied to join aluminum and galvanized steel. The intention of this approach is to make it possible to achieve a good wetting behavior while limiting the thickness of the intermetallic layer to less than 10 μm without requiring the use of chemical fluxes. The results presented in this paper were generated in experiments which were conducted with the aim of validating this hypothesis. However, these experiments were also performed with the intention of examining the potential of this technology for industrial application and exploring its flexibility. For this reason, the experimental program included different wire and base materials as well as different joint geometries. The joints were consequently analyzed by visual inspection as well as metallographic and mechanical tests.

2. Experimental procedure

A schematic illustration of the process setup is provided in Fig. 1. Both laser beams are superimposed using a beam splitter and focused through a common lens, resulting in identical angles of incidence. The cw beam is shaped to a circular spot with a diameter of 3.0 mm. It provides thermal energy to the wire as well as the base materials. The pw beam possesses a line-shaped focus of 3.5 mm × 0.1 mm. It is oriented perpendicularly to the joint, allowing the pw laser to act over the whole width of the seam. The laser beams are focused on the surface of the aluminum sheet and oriented with a lateral offset of 0.2 mm toward the aluminum material. The pw laser is operated at a repetition rate of 10 kHz. Shield gas is supplied to the process zone at a rate of 20 l/min to prevent a renewed oxidization of the aluminum during the joining process. As shown by Donst (2012), this will also support the thermochemical decomposition of the oxide layer. Consumable wire materials are fed into the process at a variable velocity v_{wire}. Unless stated otherwise, all experiments were performed at a process speed of $v_{\text{join}} = 0.7$ m/min.

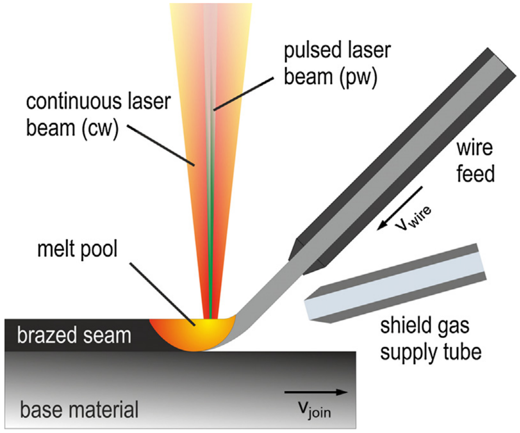

Fig. 1. Schematic setup of the joining process.

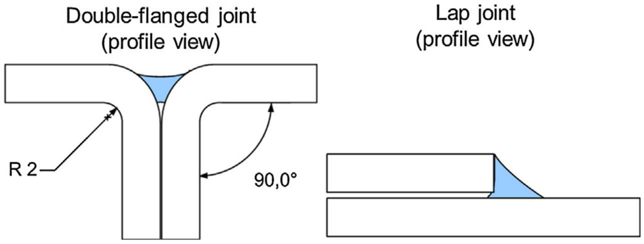

Fig. 2. Joint geometries.

Table 1
Wire materials.

Alloy	Melting range (°C)	
AlSi5	573–625	(Lincoln Electric, 2014)
AlSi12	573–585	(Lincoln Electric, 2014)
ZnAl2	382–407	(Grillo, 2014)

Experiments are performed on two different joint geometries in order to examine the geometrical flexibility of the double beam approach. The basic geometry of both joint types is depicted in Fig. 2. The dimensions of the blanks are 60 mm × 150 mm. The samples are clamped in a zero-gap configuration using a simple vice for double-flanged joints and two knee levers mounted to a backplate for lap joints. The lap joints are processed at a lateral inclination of 25°.

To examine the flexibility of the double beam method regarding the choice of materials and to examine the influence of different alloys on the resulting joint, the experimental program includes four different base materials as well as three different consumables. Lists of these materials, including some of their key properties, are provided in Tables 1 and 2.

As can be derived from the alloy designation, both types of steel sheet are galvanized, which is typical for potential applications in the automotive industry. The DX51D + Z sheet is hot-dip galvanized

Table 2
Base materials.

Alloy	Material no.	Thickness (mm)
AlMgSi1	EN AW-6082	1.0
AlMg3	EN AW-5754	1.0
DX51D + Z275	1.0226	0.75
DC04 + ZE75/75	1.0338	0.75