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Effect of dual laser beam on dissimilar welding-brazing of aluminum to galvanized steel

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In this investigation, the joining of two types of galvanized steel and Al6022 aluminum alloy in a coach peel configuration was carried out using a laser welding-brazing process in dual-beam mode. The feasibility of this method to obtain a sound and uniform brazed bead with high surface quality at a high welding speed was investigated by employing AlSi12 as a consumable material. The effects of alloying elements on the thickness of intermetallic compound (IMC) produced at the interface of steel and aluminum, surface roughness, edge straightness and the tensile strength of the resultant joint were studied. The comprehensive study was conducted on the microstructure of joints by means of a scanning electron microscopy and EDS. Results showed that a dual-beam laser shape and high scanning speed could control the thickness of IMC as thin as 3 μm and alter the failure location from the steel-brazed interface toward the Al-brazed interface. The numerical simulation of thermal regime was conducted by the Finite Element Method (FEM), and simulation results were validated through comparative experimental data. FEM thermal modeling evidenced that the peak temperatures at the Al-steel interface were around the critical temperature range of 700–900 °C that is required for the highest growth rate of IMC. However, the time duration that the molten pool was placed inside this temperature range was less than 1 s, and this duration was too short for diffusion-control based IMC growth.

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1. Introduction

Zinc-coated steels have met the present auto industry requirements by providing an effective combination of high strength, low yield-to-tensile ratio, as well as good corrosion resistance. However, to control global warming, the U.S. Environmental Protection Agency requires significant improvements in fuel efficiency. One of the best solutions to attain this requisite is to reduce the car's weight by fabricating light weight alloys like Al materials for application in the skin panels. Nevertheless, to maintain car crashworthiness, aluminum alloys can substitute for steel structures to only some extent. Thus, hybrid steel-aluminum structures have been introduced as a good replacement for many common all-steel body structures, making the joining of aluminum to steel inevitable [1].

Regarding the joining of multi-component structures, the conventional joining processes have been studied and developed, including mechanical joining with rivets or screws, adhesive bonding, friction stir welding, explosive welding, and fusion welding [2]. Restrictions like slower assembly cycle and visibility of the rivets has made mechanical joining undesirable specifically in shell parts [3]. Solid state welding processes are extremely limited to the shape and size of joints so that only simple geometries such as butt and overlapping can be joined [4]. On the other hand, fusion welding of such dissimilar metals has posed many issues. A significant difference exists in the thermal and physical properties between Al and steel, such as thermal conductivity, thermal expansion, large differences in melting temperatures (>800 °C), and the nearly zero solid solubility of Fe in Al and vice versa. These differences caused the development of undesirable brittle intermetallic compounds (IMCs) along the interface in the early stages of welding. It has been shown that an IMC layer with higher thickness reduces the strength of the joint significantly because of its low stress intensity factor as well as high crack propagation rate [5]. However, it was reported that the formation of IMC is useful to improve the wettability between Al and Fe, and good mechanical properties can be achieved if the thickness of the IMC layer is less than 10 μm [6].

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Thus, controlling the formation and growth of the Fe-Al IMCs is the current challenge of joining Al to steel.

In the last decade, a laser joining technology was developed to minimize the issues posed by the traditional fusion welding methods. Laser provides benefits like concentrated energy density in small areas with a smaller heat affected zone, the feasibility of automation, and the ability of reaching a high scanning speed [7]. In the subcategory of laser joining, recently a concept of laser brazing was proposed for the joining of similar and dissimilar metals. A liquid/solid state was utilized to join Al-steel where the diffusion of elements through the interface was limited and the reaction rate compared to the liquid/liquid state laser welding was minimized. Based on this concept, considerable attempts have been carried out for joining Al-steel structures by lasers. These studies involved a hybrid welding/brazing with a filler wire in which a fusion welding joint was formed at the aluminum side and a brazing joint was created at the steel side of the weld bead. In this type of joining technology, several solutions have been reported to restrict the growth of IMCs at the aluminum-steel side of the bead to sub-critical values [8,9]. The process temperature particularly at the interface of Al-steel is shown to have a huge effect on the growth of IMCs. Therefore, monitoring the thermal regime during welding as well as the resulting numerical prediction should be of a great importance. Until now, only very limited literature in the field of numerical simulation models has been proposed to predict the temperature profile during Laser Welding-Brazing (LWB) [10–12]. The thermal regime of LWB of Al 6016 to non-galvanized steel at the interface was estimated by Peyer et al. [10]. The correlation between the maximum temperature at the Al-steel interface, welding speed, and IMC thickness was obtained. Another study based on the temperature measurement and numerical simulation, carried out by Mathieu et al. [11], showed that there was a specific temperate range in which the IMC layer had the greatest rate of growth. Applying the results obtained by numerical simulation, minimizing the process temperature, and process duration made it possible to keep the thickness of the IMC layer below a critical value.

Most studies of the laser welding/brazing process have been carried out by using a single laser beam. Yan et al. [13] observed that application of a dual beam Nd:YAG laser could generate an acceptable joint of steel/aluminum sheets and effectively reduce the presence of blowholes. As shown by Shen et al. [14] a tandem beam used for laser welding of dissimilar titanium alloys had higher strength and elongation than a single beam for laser welding. It was found that the dual-beam LWB compared to a single laser beam improved the process stability. LWB made a visually better-looking weld bead with a larger width. Furthermore, this weld bead increased the shear strength of the joint [15]. Li et al. [16] used cross-beam LWB to join the Zn-coated steel to a Mg alloy in a lap joint configuration. They revealed that the cross-beam mode was superior in reducing the wetting angle and promoting the spread of filler material with respect to the single beam mode.

The coach peel joint, due to the wider space between its panels in comparison to the other types of joints, needed to have a larger laser beam spot to cover the groove appropriately. As the laser spot size increased, the laser power should increase in order to have a high welding speed. Filliard et al. [17] investigated the high speed of LWB of steel to aluminum by means of single laser beam. They used the spot size of 3 mm and laser power of 6 kW in the welding speed of 4–6 m/min. Another approach to compensate for the lower laser power and larger spot size was to decrease the welding speed. Shabadi et al. [18] conducted experiments on the beam diameter of 1.6 mm with a laser power of 1.5 kW and welding speed of 2 m/min. Recently, some investigations were carried out on the feasibility of different laser beam arrangements and their effects on the quality of the weld. Frank [19] reported that a combination of continuous and pulsed laser beams in a circular-and-line-shaped mode perpendicular to the weld provided a good wetting at a welding speed of 3.6 m/min. Recently, the Laserline company [20] announced a new laser head that generates a triple-spot laser for welding/brazing of similar and dissimilar materials. In this design two smaller laser spots are used to preheat the materials to be welded, and the laser spot in the middle is used to melt the filler material. Another beam arrangement that has good compatibility with the geometry of a coach peel joint is the dual laser beam that has been studied only on welding of similar aluminum [21] and steel [22] joints. This type of laser beam can deliver wider beams either across the weld groove or along it.

However, there has been no comprehensive research done on understanding the correlation between either measured or predicted temperature profiles at the brazed joint interfaces and IMC thickness as well as joint mechanical properties at an elevated scanning speed. In this study, a high speed LWB process by means of two types of dual laser beam arrangement modes (cross and in-line) to join aluminum alloy to galvanized steel (hot-dip and electrogalvanized) in a coach-peel configuration was conducted. The surface quality and edge variations of the obtained beads and the effect of IMC layer thickness on mechanical properties of the joint were also investigated. Finally, the numerical simulation using commercial software ANSYS was proposed to predict the temperature regime through either a weld or brazed interface.

2. Experimental procedure

The base metal used in this study was a 1.2 mm thick aluminum 6022 alloy coach peel panel and two types of galvanized low carbon steel coach peel panels with a thickness of 0.65 mm (Hot-dip galvanized steel (HDG) and electrogalvanized steel (EG)). The filler wire used in this study was Al4047 with 1.6 mm in diameter. The chemical composition of materials are listed in Table 1.

An IPG fiber laser of 4 kW in power was used to carry out the welding of dissimilar materials (Al to steel). A brazed coupon is shown in Fig. 1. The dual laser beam modes (cross-beam and in-line beam) were used with respect to the center of joint, and a schematic diagram of dual beams are shown in Fig. 2. To obtain a dual laser beam shape, an optical beam splitter was mounted inside the laser head that split the laser beam in two beams with a power distribution of 50/50 on each side. The generated dual spots had the same diameter of 1.45 mm at the defocused plane and generated beams that had a 22.66% overlap of the spot. In an experimental setup, a laser head and Binzel wire feeding system were mounted on a 6-axis KUKA robot. The shielding gas used to protect the molten pool from an ambient atmosphere was pure argon with the flow rate of 25 SCFH. A schematic view of the experimental setup is illustrated in Fig. 3 with the horizontal distance from the tip of shielding gas tube to the laser beam, the tilt angle of gas shielding tube, and the angle of filler wire. To protect the optics from direct reflections of laser beam, the laser head was also tilted at 5°. All experiments were carried out at a welding speed of 60 mm/s and wire feed rate of 70 mm/s. Because of the differences in beam mode and their energy distribution, the magnitude of optimum laser power for dual cross beam and dual in-line beam were selected as 3.2 kW and 3.4 kW, respectively.

To obtain thermal cycles around the bead at both sides of Al and steel, the number of thermocouples were mounted close to the welded/brazed area. The temperature along the bead was measured by K-type thermocouple. The National Instruments data acquisition system was used to capture temperature at every 0.1 s. To quantify the surface roughness of the obtained beads, the surface profile of the bead was measured by the Micro Photonic Nanovea ST400/3D non-contact profiling device to ensure the

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