Materials and Design 58 (2014) 265–276

Contents lists available at ScienceDirect

Materials and Design

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

Pore formation mechanism and its mitigation in laser welding of AZ31B magnesium alloy in lap joint configuration

Masoud Harooni [a], Blair Carlson [b], Brian R. Strohmeier [c], Radovan Kovacevic [a,*]

[a] *Research Center for Advanced Manufacturing, Mechanical Engineering Department, Lyle School of Engineering, Southern Methodist University, 3101 Dyer Street, Dallas, TX 75205, USA*
[b] *General Motors R&D Center, Warren, MI 48090-9055, USA*
[c] *Thermo Fisher Scientific, 5225 Verona Road, Madison, WI 53711, USA*

ARTICLE INFO

Article history:
Received 30 September 2013
Accepted 23 January 2014
Available online 4 February 2014

Keywords:
Laser welding
Magnesium alloy
Preheating
Oxide layer
Porosity
X-ray photoelectron spectroscopy–reflected electron energy loss spectroscopy

ABSTRACT

Magnesium is one of the lightest structural metals that has been used in different industries such as automobile, aerospace and electronics. However, in fusion joining of magnesium alloys, porosity is one of the main drawbacks to achieve a weld with desirable properties. The oxide layer existing on the surface of magnesium alloy is one of the causes of pore formation in the weld bead. In the current study, a fiber laser with a power of up to 4 kW is used to weld samples in a zero-gap lap joint configuration. Two groups of samples are studied: as-received (AR) surfaces (where an oxide layer remains on the surface) and treated surfaces. The surface treatment includes two techniques: mechanically removed (MR) and the use of a plasma arc (PA) as a preheating source. Also, a separate set of experiments are designed for preheating samples in a furnace for comparison with the PA-treated results. To reveal the chemical compositions of the welds and metal sheet surfaces, an energy dispersive spectroscopy (EDS) is performed. Surface chemical compositions are tested by X-ray photoelectron spectroscopy-reflected electron energy loss spectroscopy (XPS-REELS) to characterize the surface composition on AR and PA-treated samples. The dynamic behavior of the weld pool and laser-induced plasma plume is monitored in real-time using a high speed CCD camera to investigate the stability of the laser welding process. The presence of the oxide layer at the faying surface of two overlapped sheets results in an unstable process. The obtained results reveal that the preheating procedure can effectively mitigate pore formation at the interface of the two overlapped sheets.

1. Introduction

The manufacturing of light-weight components is one of the most important aspects in reducing fuel consumption and consequently lowering the production of greenhouse gases. Light-weight components improve the quality of human life from two aspects: providing an economic means of transportation and a cleaner environment [1,2]. It is reported that reducing the mass of an automobile by 10% will reduce 7% of the fuel consumption [3]. The automotive industries achieved an average 25% reduction in fuel consumption between 1990 and 2005 [4]. Magnesium is one of the lightest structural metals being used in different industries such as automotive, aerospace, and electronics [1], and it provides an opportunity for continued mass reduction in the automotive industry. The density of magnesium is 36% less than aluminum and 78% less than steel. Therefore, it is one of the most ideal metals for lightening purposes [5]. It has also the best strength-to-weight ratio, good impact resistance, high thermal conductivity, and high damping capacity [6]. Magnesium is called “green engineering material” due to its contribution to energy savings and its ability to be recycled [1]. Demand results in increasing consumption of this metal worldwide, mainly in North America, Europe, and Japan. [4,7].

Magnesium alloy consumption takes different shapes and forms for different industries [1]. To satisfy the production of different shapes to fit industry requirements, it is essential to study the joining processes of this alloy [8]. Different joining processes such as laser welding [1,9], arc welding [1], hybrid laser-arc welding [1,10], friction stir welding [1,11], resistance spot welding [1,12], and electromagnetic pulse welding [1,13] are used for welding magnesium alloys. Among these processes, laser welding is paid more attention due to its advantages. High power density, low heat input, and consequently a narrow fusion zone and HAZ, a high depth-to-width ratio, and suitability for joining complex shapes are some of the advantages of laser welding [1]. Different laser sources are used to weld magnesium alloys such as fiber laser

---

* Corresponding author. Tel.: +1 214 768 4865; fax: +1 214 768 0812.
E-mail address: kovacevi@lyle.smu.edu (R. Kovacevic).

http://dx.doi.org/10.1016/j.matdes.2014.01.050
0261-3069/

[14,15], Nd:YAG laser [16], CO_2 laser [17,18], diode laser [2], and disk laser [19].

Pore formation is one of the main issues in welding magnesium alloys [1,9]. Generated pores in the weld bead deteriorate the mechanical properties of the weld, especially the tensile strength. Therefore, it is important to understand the pore formation mechanisms and their mitigation procedures during the welding process. Different mechanisms cause pore formation in the laser welding process, including hydrogen pores [1,20], unstable keyhole [21], pre-existing pores, surface coating [1,22], gas entrapment [1,23], and alloy elements with a low vaporization point [24].

The only gas that can be dissolved in molten magnesium is hydrogen [9]. Hydrogen pores are caused by the difference in solubility of hydrogen in solid and liquid magnesium. As molten magnesium solidifies, hydrogen solubility sharply decreases and rejects the hydrogen gas resulting in pore formation in the weld bead [1]. Mikucki and Shearouse [20] concluded that the hydrogen content should be kept as low as possible in magnesium in order to prevent pore formation during the solidification process [20].

An unstable keyhole is one of the causes of pore formation in the laser welding process [9]. Keyhole stability depends on properties of the molten metal such as surface tension and vapor pressure [25]. The vapor pressure inside the keyhole forces the keyhole to be open; whereas, surface tension tends to close the keyhole [25]. In laser welding of aluminum alloys, the keyhole oscillates and contributes to pore formation [26]; However, magnesium has a much higher vapor pressure and lower surface tension than aluminum alloys [25] resulting in higher stability of keyhole during the laser welding process.

Pre-existing pores are another cause of pore formation in the weld bead of magnesium alloys [1,9]. The initial high gas content in magnesium alloys is one of the reasons for pore formation in the weld bead, especially in alloys that are die-casted [9]. The welding procedure provides the condition for the pores to coalesce and form larger pores [1,9,25]. It is noted that a higher welding speed reduces the available time to form and grow pores, resulting in fewer pores in the weld bead [25].

Gas entrapment in the molten pool is another reason for pore formation in the weld bead [9,23]. Pores created by this mechanism are a result of the oscillation of the surface of the molten pool that entraps gases from the air [23]. The oscillation of the surface happens in the laser welding of magnesium because magnesium has an extremely low surface tension and viscosity [9]. In order to prevent gas entrapment in the laser welding of magnesium, it is suggested to use a shielding gas with the appropriate parameters [23].

Surface coatings are another cause of pore generation in the weld bead [1]. The porous oxide layer easily absorbs moisture from the atmosphere [9], which contributes significantly to the formation of porosity and cracking in the Mg laser weld [1,9]. To prevent defects from forming due to the oxide layer, most researchers suggest removing the oxide mechanically prior to welding [9]. However, this method is time consuming and typically non-economical for industrial applications.

In order to evaluate the influence of the oxide layer on the weld quality, different surface conditions are introduced: as-received (AR) with the oxide layer remaining on the surface, mechanical removal (MR) of oxides by sand paper, and a heat-treated surface by plasma arc (PA). To the best of our knowledge, no research has investigated the mechanism and mitigation of pore formation caused by the oxide layer on the surface. In a separate experiment, a furnace was employed to compare results with the plasma arc preheating process. The process is significant in the mitigation of pore formation in laser welding of magnesium alloy. Observations include optical microscope, SEM-EDS tests, XPS test, REELS test, and tensile testing. A high speed CCD camera assisted with a green laser as an illumination source was used to record the images of the weld pool and laser-induced plasma plume in real-time to verify the stability of laser welding process.

2. Experimental procedures

A 4-kW fiber laser is used to weld two sheets of AZ31B magnesium alloy in a zero-gap lap joint configuration. A lap joint configuration is selected because of its application in the auto industry [27]. The experimental setup including a 6-axis robot and a welding laser head is shown by the schematic view in Fig. 1. AZ31B magnesium alloy coupons in the size of 85 × 50 × 1.5 mm are cut using an abrasive water-jet cutting machine. The nominal chemical composition of this alloy is shown in Table 1. To investigate the effect of the oxide layer on the quality of the weld, two groups of samples are introduced: as-received and treated surfaces. Samples with an existing oxide layer on the surface are called as-received (AR). Surface treated samples refer to mechanically removed (MR) oxides, plasma arc treated (PA) surfaces, and

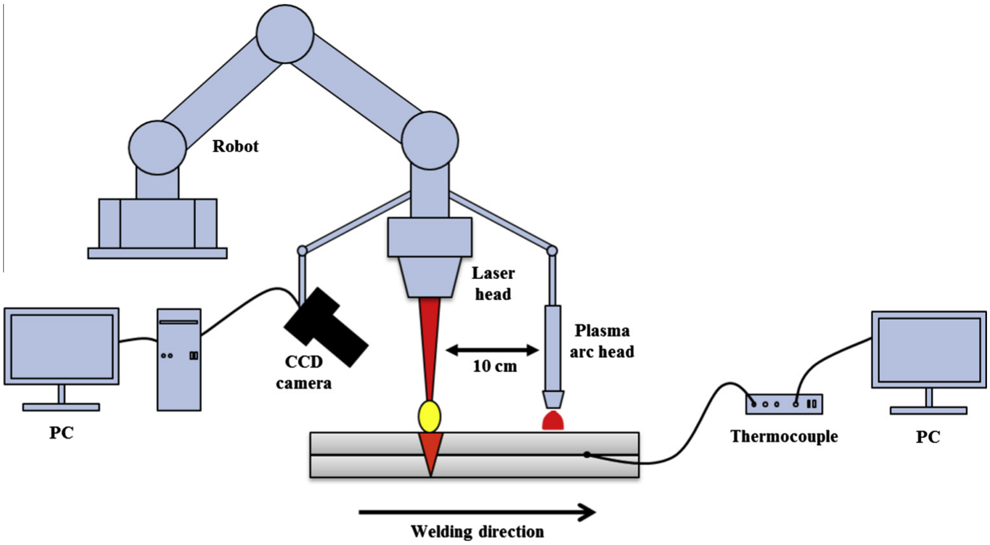

Fig. 1. The schematic view of the experimental setup.