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Nd:YAG laser welding of aerospace grade ZE41A magnesium alloy: Modeling and experimental investigations

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Abstract

Keyhole formation as well as the geometry of weld profiles during Nd:YAG laser welding of ZE41A-T5 were studied through combining various models and concepts. The results indicated that weld width and fusion area decrease with increasing welding speed. In the case of partially penetrated welding, penetration depth decreases with increasing welding speed. Also, the model predicted that excessive decrease in laser power or increase in defocusing distance decreases surface power density, thereby changing the welding mode from fully penetrated keyhole, to partially penetrated keyhole, and then to the conduction mode. The predicted conditions for keyhole stability and welding modes as well as the weld profiles for various processing conditions were validated by some selected welding experiments. These experiments included studying the effects of welding speed, laser power, joint gap and laser defocusing on the weld geometry of 2- and 6-mm butt joints or bead-on-plates of ZE41A-T5 sand castings using a continuous wave 4 kW Nd:YAG laser system and 1.6-mm EZ33A-T5 filler wire. Good agreements were found between the model predictions and experimental results indicating the validity of the assumptions made for the development of the model.

Keywords: Laser welding; Modeling; Mg sand casting; Filler wire; Keyhole mode

1. Introduction

Laser welding is in general a keyhole-mode fusion welding technique that provides line-heating source through the material thickness [1,2]. Compared with conventional fusion welding processes, laser welding produces higher penetration depth in a single pass [2]. The keyhole can be described as a vapor capillary tube surrounded by a molten metal [3] and is formed when the laser power absorbed by the metal is greater than the material specific intensity threshold [3,4]. This means that the critical intensity limit for keyhole formation must be overcome by the intensity of the laser beam. The presence of such conditions results in the creation of a moving keyhole surrounded by a molten metal due to the absorption of incident laser beam [5]. Because of the high welding speed [3], the molten metal is rapidly solidified behind the moving keyhole creating the joint between the welding parts (Fig. 1). The heating power is obtained by focusing the laser beam into a very small spot that provides a very high power density [2,3,5,6]. The range of power density that creates the keyhole is from 10^3 to 10^5 W mm^{-2}, and above this range cutting and drilling are usually achieved [2].

The stability of the keyhole depends on the force balance between the keyhole wall and the molten metal around it, and this can be described by the following equation [5]:

$$P_v = P_\sigma \tag{1}$$

Where P_v is vaporization pressure, and P_σ surface tension.

This means that the stability of the keyhole depends on the force balance between the vapor pressure and the surface tension pressure. The vapor pressure tends to open the keyhole whereas the surface tension pressure tends to close it. The above findings have been confirmed by Zhao and co-workers [4,7] and Punkari et al. [8]. If the laser intensity overcomes the threshold intensity of the material, the keyhole forms and induces two main absorption mechanisms; Fresnel and plasma absorption. The Fresnel absorption can be divided into the first Fresnel absorption and multiple reflections. The first Fresnel absorption represents the first absorption occurring due to the first interaction of the laser ray with keyhole wall. The temperature inside the keyhole will be much higher than the evaporation temperature at the key-

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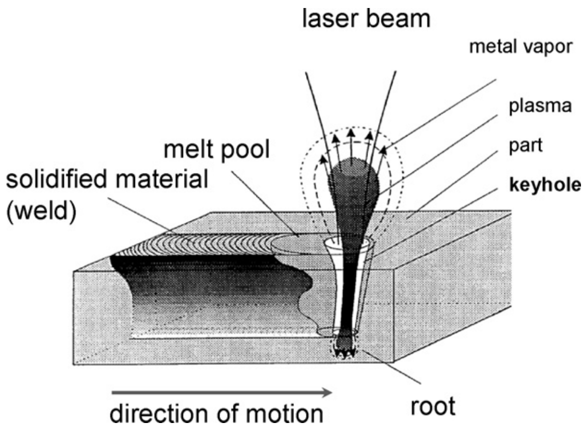

Fig. 1. Laser welding in the keyhole mode.

hole wall which leads to the formation of ionized gases which absorb energy from the reflected laser rays. The energy balance between these effects and the heat loss through the keyhole wall will determine the keyhole profile.

A useful method to describe the keyhole profile in a plane parallel to welding direction for the front and rear walls during CO_2 laser welding of steel was proposed by Kaplan [9]. A conical shape was assumed for the keyhole for the purpose of calculating the multiple reflections of the laser ray. Also, only normal incidence absorption (ray perpendicular to the keyhole wall) during multiple reflections was considered in the calculations. The plasma absorption was estimated using the value of the intensity that is left after undergoing multiple reflections and by defining the mean path of the rays as one and half times the depth of a blind keyhole. The intensities obtained for multiple reflections and plasma were both assumed to be for the same layer at the first Fresnel absorption (the first interaction of the laser ray with the keyhole wall). Lampa et al. [10] modeled the weld pool geometry generated during CO_2 blind laser welding of steel by applying Kaplan's [9] method. They calculated the top weld width and assumed the bottom weld width to be half of the top weld width for blind keyhole-mode welding based on the experimental observations. To account for the effect of thermocapillary (Marangoni) flow, Lampa et al. [10] assumed that the thermal conductivity on the top is 2.5 times the real thermal conductivity, and they corrected the source strength on the top of the keyhole accordingly. The penetration depth was calculated by dividing the total power absorbed by the keyhole by the average line source strength, using the artificial thermal conductivity value at the top, and the real thermal conductivity value at the bottom.

The Fresnel absorption and reflection in the keyhole were studied by Jin et al. [11]. Glass was used to capture the keyhole profile in a plane parallel to the welding direction, and the multiple reflections and the laser absorption inside the asymmetric keyhole were analyzed using geometrical optics theory. The plasma absorption was avoided in the above study since the glass GG17 used had very high ionization energy and thus plasma is difficult to form. On the other hand, Solana and Negro [12] studied the effect of multiple reflection and plasma on the blind keyhole profile. They developed a numerical model with an initial keyhole having conical shape based on assumed keyhole top radius and penetration depth. It was found that the keyhole profile varies with the Fresnel and plasma absorption values; however, the energy conservation at the keyhole wall was not considered.

In the present work, Kaplan's [9] and Lampa et al.'s [10] models were modified and combined with the calculation methods of the multiple reflection [11] and plasma absorption [12] to calculate the weld geometry profiles. Although the keyhole in the actual process is asymmetric in the plane parallel to welding direction, it is symmetric in the plane perpendicular to welding direction. In addition, the perpendicular plane also reveals the weld geometry profile, and thus it was used in the calculations of this study. This was achieved by calculating the energy balance at each layer of the keyhole and by registering the location of each multiple reflection and plasma absorption in the corresponding layer. A correction factor was used, instead of artificial thermal conductivity values, to estimate the effect of the widening of the weld width due to the thermocapillary flow. This factor was used to correct the source strengths based on the experimental investigation during laser welding of Mg alloy. Finally, the modeling results were verified by experiments.

2. Experimental procedures and materials

2.1. Materials and equipment

The experimental material was aerospace grade sand cast ZE41A-T5 (Mg–4.2Zn–1.2Ce–0.7Zr) magnesium alloy. The cast plates had sizes of approximately 300 mm × 150 mm × 3–7 mm. The plates were cut into four small pieces for laser welding, each with approximate sizes of 150 mm × 75 mm × 3–7 mm. The magnesium castings were then machined to 2 and 6 mm thicknesses. The joint faces were also machined along the length for all the specimens. Prior to laser welding the joint faces and their surroundings were carefully cleaned by acetone to remove any contaminations.

The laser welding machine used in this study is a continuous wave (CW) 4 kW HL4006 Nd:YAG (neodymium-doped yttrium aluminum garnet) laser system equipped with an ABB robotic and magnetic fixture system. A focal length of 150 mm and a fiber diameter of 0.6 mm were employed. Helium was used to shield the top surface and argon for the bottom surface of the workpieces as shown in Fig. 2. The flow rates were 18.9 and 21.2 l min^{-1} (40 and 45 ft^3 h^{-1}) for the top and bottom surfaces, respectively. The shielding gas, He, was directed to the top surface of the workpiece at an angle of 30° (with the horizontal) and Ar was vertically and uniformly directed to the bottom surface. The workpieces (butt joint) were positioned and clamped in a fixture with various gap size from 0 to 0.6 mm. Defocusing range was between 0 and −4 mm with 0.45 mm focal spot diameter.

A filler wire of EZ33A-T5 (Mg–3Re–2.5Zn–0.6Zr) Mg alloy with 1.6 mm diameter and 990 mm length was used through a wire feeding mechanism. Laser welding using filler wire is getting more attention since it might solve many of the problems facing autogenous welding. The most important advantages of using filler material include improving weld properties, increasing the gap between the welding parts, and welding thick sections using a multi-pass technique. Compared with other welding techniques laser welding requires less filler wire per meter of welded seam, underfill and notching effect can be overcome using filler wire, and finally the porosity of the welded joint can be reduced using filler metal [2,3]. The filler wire was positioned at the intersection of laser beam and top surface of the workpiece. A delivering angle of 60° was used between the filler and the laser beam axis to reduce the contact area between them. During laser welding, the workpieces were stationary while the laser beam scanned at a power value between 2.5 and 4 kW and a speed from 2 to