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Effect of power distribution on the weld quality during hybrid laser welding of an Al–Mg alloy

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ABSTRACT

This paper treats of the analysis of the effect of arc and laser powers on the quality of the arc assisted fiber laser welding of an Al–Mg alloy in the butt configuration. Grain size, weld geometry defects, porosity, and magnesium loss were measured. Magnesium content of the fused zone decreased as the laser power increased while the porosity increased with laser power. Microhardness profiles and tensile properties were explained on the basis of the joint microstructure and defects and related to the power distribution. The porosity level and Mg content in the fused zone affected both tensile strength and ductility. The power distribution that stabilized the welding process and minimize the weld porosity was defined.

1. Introduction

For many years, both arc and laser welding have been the dominant joining methods of metals [1,2]. Conventional electric arc welding processes show important advantages due to their availability, energy efficiency, simple technology and low costs of operation but meanwhile have some disadvantages such as process instability and slowness, a wide heat-affected zone (HAZ) and weldment distortion. In the same way, laser welding has some limitations and problems such as higher power consumption, high cost of equipment, poor bridgeability, strict requirements concerning the laser beam adjustment and sample alignment [3,4]. Besides, laser welding generates welding bead with high pores/voids and is generally more difficult to apply to aluminum alloys, such as 5000 magnesium series. Those aluminum alloys, whose major alloying element is Mg, are desired for their excellent corrosion resistance, substantial strength and weldability [5–7]. Laser beam welding of Al alloy is particularly critical owing to high thermal and electrical conductivity, large thermal expansion, lower viscosity and high reflectivity of the metal [8]. During laser welding, the low melting point of the alloying elements such as magnesium or zinc easily makes them to vaporize [9]. Elements vaporize, escape through the keyhole, and pull molten material along with them, leaving weld voids and spatter in their wake. A homogeneous liquid forms prior to solidification when intermetallic compounds can form [10]. The formation of porosity, solidification cracking, and modification of the mechanical properties is the result of the element loss [11,12]. Recently the laser–arc hybrid welding process has proved to be successfully to overcome problems commonly encountered during either laser or arc welding. Hybrid welding couples processes arc and laser welding in a single process. Hybrid welding overcomes the disadvantages in laser welding and in arc welding while keeping advantages of both processes. Lower energy input is obtainable compared to arc welding; therefore the welded structure has less thermal distortions and residual stresses. Moreover the hybrid laser arc welding (HLAW) reduces the need for edge preparation; it generates narrower heat-affected zone lower porosity while increasing welding speed and productivity [13,14].

The laser-to-arc powers ratio also can play a significant but not enough clarified role in the hybrid welding process. That ratio determines which one between the laser and the arc is the dominant welding source and which one has the greater influence on the change in penetration depth and the width of the weld pool. El Rayes et al. reported that increasing the ratio of arc to laser power, for constant CO_2 laser power levels of 8 and 4 kW, causes the narrow lower portion of the hybrid weld cross-section to increase in length. However, it appears to be a minimal effect on the total depth of the weld pool [15]. The change of the hybrid

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Nomenclature

ACZ	arc crown zone
BM	base material
CZ	crown zone
DCZ	depth of crown zone (mm)
DLZ	depth of laser zone (mm)
DU	depth of underfill (mm)
E	elongation (%)
EDS	energy dispersive spectrometry
FGZ	fine grain zone
FZ	fused zone
GMA	gas metal arc
HAZ	heat affected zone
HLAW	hybrid laser–arc welding
LZ	laser zone
MIG	metal inert gas
Nd:YAG	neodymium:yttrium aluminum garnet
OM	optical microscope
P_L	laser power (W)
P_{MIG}	arc power (W)
P_{TOT}	total power of the heat sources (W)
R	ratio between laser and MIG power
SEM	scanning electron microscope
TS	tensile strength (MPa)
WCZ	width of crown zone (mm)
WFR	wire feed rate (mm/min)
WLZ	width of laser zone (mm)

weld geometry according to laser/arc power ratio also alters mechanical properties of the joint [16]. Chen et al. [17] investigated the transition between conduction mode and keyhole mode with different energy ratios between laser and arc of CO_2 laser TIG paraxial hybrid welding. Moreover, a series of CO_2 laser–metal inert gas arc hybrid welding experiment investigated the effects of laser/arc energy ratio and groove parameters on the shape and microstructure of weld. In particular, Gao et al. showed that increasing arc current and groove cross-section area can reduce the size of laser and arc zone by enhancing the uniform of energy distribution in the molten pool [18]. Detail studies on the interaction between laser radiation and electric arc used in hybrid heat source are available. During the pulsed laser–arc welding process the extension of arc plasma column into laser keyhole gives the pressure to the inner keyhole wall, which hinders the keyhole-collapse. Moreover, the surface tension of the liquid metal around the keyhole outlet increases due to the extension of arc column into the keyhole, which also prevents the keyhole outlet from collapsing [19]. As a synergetic effect of laser and arc the stability, the escaping ability of the gas bubbles in the weld pool increases [20,21]. Katayama et al. have reported that an increase in arc current helped to prevent significantly the internal porosity formation due to a more favorable direction of the melt flow [22].

The fiber laser beam has a wavelength of one-tenth of that emitted by a conventional CO_2 laser and it ensures high-speed results even when processing reflective materials, such as aluminum, and combination of dissimilar light metals [23,24]. Thus far, this new kind of laser has showed higher efficiency in comparison to conventional solid-state (CO_2 and Nd:YAG) laser. During fiber laser–MIG hybrid welding, the pure argon shielding gas promotes the ionization and stabilization of the arc. Therefore, the fiber laser hybrid welding has demonstrated to warrant a more stable process. A common result in the performed investigation indicated that the strength loss of the joint strongly depends on magnesium loss, the decrease of the precipitates and the grain size growth. The porosity is also the main reason for the decrease of both tensile and fatigue strength [25,26].

In this study, 3 mm thick AA5754-H111 aluminum alloy sheets were joined in the butt configuration using a fiber laser and a metal inert gas (MIG) arc welding process. The quality characteristics of weld bead geometry, macro- and microstructure, microhardness and defect formation of the joints were analyzed and discussed with respect to the power distribution, which is an alternative to the classic process parameters approach [27]. The scopes of this article is to give a detailed characterization of the weld metallurgical and mechanical properties and to relate phenomena like segregation and porosity to the arc and fiber laser power. The process condition to obtain good mechanical properties and low-porosity weld were identified. Eventually, recommendation for a stable welding process was given.

2. Laser and experimental set-up

The base material used in this study was an AA5754-H111 plates whose thickness was 3 mm. AA5754-H111 alloy is one of the 5XXX series non-age hardenable aluminum–magnesium (Al–Mg) alloy whose magnesium is the major alloying element. The suffixes H1 indicate the strain-hardened condition and the number following this designation indicates the degree of the strain hardening. Prior to welding, the Al alloy was in annealed and recrystallized condition. The wire was the commercial ER5356 one. Chemical compositions of the base metal and the filler wire are listed in Table 1.

The welding experiments of AA5754-H111 were carried out by an Ytterbium Laser System (IPG YLS-4000; maximum output power is 4 kW) in combination with MIG welding machine (GENESIS 503 PSR). The welding layout is depicted in Fig. 1. The experiment configuration was laser leading, which means that the laser beam is the primary heat source while the arc is the assisting heat source. Argon was the shielding gas. Detail information on the hybrid laser/MIG welding equipment are in Table 2.

The joint was in butt configuration. The laser power (P_L), wire feed rate (WFR), and arc power (P_{MIG}) varied accordingly with the following experimental plan, The P_L was constant while the P_{MIG} varied on three levels, the welding speed was 3.5 m min^{-1}. The arc power (P_{MIG}) is the product of the arc current intensity (*A*) and the arc voltage (*V*). *R* indicates the ratio between the P_L and the

Table 1
Chemical compositions of BM (Al 5754-H111) and filler wire (ER5356), (wt%).

Composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
5754-H111	0.4	0.4	0.1	0.5	2.6–3.6	0.3	0.2	< 0.15	Balance
ER5356	0.25	0.4	0.05	0.1–0.2	4.5–5.5	0.1–0.2	0.1	0.15	Balance