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An investigation on capability of hybrid Nd:YAG laser-TIG welding technology for AA2198 Al-Li alloy

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Abstract

This paper surveys the capability of the hybrid laser-arc welding in comparison with lone laser welding for AA2198 aluminum alloy experimentally. In the present research, a continuous Nd:YAG laser with a maximum power of 2000 W and a 350 A electric arc were used as two combined welding heat sources. In addition to the lone laser welding experiments, two strategies were examined for hybrid welding; the first one was low laser power (100 W) accompanied by high arc energy, and the second one was high laser power (2000 W) with low arc energy. Welding speed and arc current varied in the experiments. The influence of heat input on weld pool geometry was surveyed. The macrosection, microhardness profile and microstructure of the welded joints were studied and compared. The results indicated that in lone laser welding, conduction mode occurred and keyhole was not formed even in low welding speeds and thus the penetration depth was so low. It was also found that the second approach (high laser power accompanied with low arc energy) is superior to the first one (low laser power accompanied with high arc energy) in hybrid laser-arc welding of Al2198, since lower heat input was needed for full penetration weld and as a result a smaller HAZ was created.

Keywords: laser-TIG hybrid welding, laser welding, A2198 aluminum alloy, macrosection, microstructure, microhardness.

1. Introduction

The development and application of laser welding technologies in last decades have led to substantial advances in manufacturing technologies in many industrial sectors. In fact, significant increase in productivity and product quality has been achieved together with a marked reduction in manufacturing costs. However, critical issues usually arise when dealing with thick components because high-power laser sources are required to obtain full penetration of the joints. This is of major concern especially when dealing with highly reflective materials, such as the aluminum alloys. In particular, keyhole-welding mode should be adopted to obtain high penetration depths. Transition from conduction to keyhole mode is related to the power density, *i.e.* the ratio of the laser power to the beam spot area [1]. The corresponding threshold value of this parameter depends on a number of factors, including laser beam wavelength, material properties and surface conditions. This value is around 10^6 W/cm^2 for iron-based materials while at least 50% higher ($>1.5\times10^6$ W/cm^2) for aluminum alloys, because of much greater thermal conductivity and laser radiation reflection. Moreover, it was found that even higher values ($>2\times10^6$ W/cm^2) should be used for stable welding processes in aluminum alloys [2, 3].

Conventional electric arc welding processes (such as TIG welding) have important advantages due to their availability, energy efficiency, simple technology and low costs of operation. But some disadvantages such as process instability and slowness, a wide heat-affected zone (HAZ) and weldment distortion decrease its usage in advanced applications. In the same way, laser welding, which is a keyhole fusion welding, has some limitations and problems such as higher power consumption, high cost of equipment, poor bridge ability, strict requirements concerning the laser beam adjustment and sample alignment [4, 5]. Some advantages of laser welding in comparison with conventional fusion welding processes are high welding speed, low heat input, narrow heat affected zone, low distortion, ease of automation, and negligible weld-metal reinforcement [6, 7].However, laser welding generates welding bead with high pores/voids and is generally more difficult to apply to aluminum alloys.

Within this context, hybrid laser-arc welding techniques could result in significant advantages with respect to laser welding. Hybrid laser-arc welding technique was first investigated through combining laser and TIG welding 30 years ago [7-9]. Ability of welding thick material and the ability to bridge relatively large gaps, deeper weld penetration, less deformation, higher welding speed and improvement of arc stability are some advantages of hybrid laser-arc welding compared to lone laser welding or arc welding [10-13].

Because of the benefits mentioned above, the use of hybrid laser-arc welding technologies has become more and more attractive in recent years and, consequently, the topic is of great scientific and technological interest. An overall review and a complete bibliographic survey of hybrid laser-arc welding processes were investigated by Bagger and Olsen [14]. Mirakhorli et. al [15, 16] studied the effect of laser-arc hybrid welding parameters on mechanical and metallurgical properties of cast martensitic stainless steel (CA6NM). Furthermore, several research studies have been carried out in recent years aiming to overcome the main issues related to welding of aluminum alloys by hybrid laser-arc methods [17, 22]. In particular, optimization of CO_2 laser-MIG welding in an aluminum alloy (5005) was investigated by Sujit Ghosal and Sudipto Chaki [17]. Chen Zhang et. al studied the effects of welding parameters on the porosity of hybrid laser-arc welded aluminum alloy (AA6082) and related it to the weld pool shape [21]. M. Mazar Atabaki et. al. [22] tried to address the critical issues related to multi-material welding, by joining aluminum alloy (AA6061) to advanced high strength steel (AHSS). In fact, the use of multi-material structures is one of the key strategies for lightweight design. Within this field, the ever-increasing demand for lightweight and high-strength structures persuades researchers to investigate lightweight metallic materials, such as Aluminum–Lithium (Al-Li) alloys [23]. In fact, these alloys are particularly attractive due to their lower density, higher specific strength and stiffness, better corrosion and fatigue properties if compared to conventional aluminum alloys. Thanks to these properties, significant structure weight reduction (10-15%) and stiffness increase (15-20%) can be achieved. As a consequence, Al–Li alloys are being increasingly used as structural materials in the aerospace industry. However, notwithstanding the great interest from both research and engineering communities, many aspects related to welding of Al-Li alloys still represent critical issues. These problems are mainly due to the high thermal conductivity and laser radiation reflection [24]. Conditions for keyhole formation in an Al-Li alloy (2195) were analyzed in [25]. It was found that the threshold value is about 25% lower than that of Al–Mg alloy (5454) and 40% lower than that of Al–Cu alloy. More recently, some studies have been carried out to analyze the effects of CO_2 laser welding and treatments on static and fatigue mechanical properties of Al-Li alloys for aircraft applications [26-29].

Notwithstanding the great efforts by various researchers, many aspects related to welding of Al-Li alloys are still unsolved and much more research should be carried out with the aim of analyzing the possible benefits arising from hybrid laser-arc welding. This is not a simple task because of the large number of process parameters. Within this context, numerical modeling can be helpfully applied to predict several welding features, such as the weld pool geometry. A novel computational method has been developed by Faraji et. al. [30] to predict the weld pool shape in GTA welding based on Computational Fluid Dynamics (CFD) simulations. A modified method has been also developed to analyze hybrid laser-TIG welding [31, 32] and predictions have been compared with experimental results. In addition, the model has been used to analyze the effects of welding parameters in hybrid laser-TIG welding of an aluminum alloy systematically (AA6082).

In this study, the weldability of a commercial Al-Li alloy (AA2198) was systematically analyzed by using both Nd:YAG laser welding and hybrid laser-arc welding (HLAW). In particular, bead-on-plate welds were made by using 3 mm thick plates and the effects of welding parameters were investigated. It was found that keyhole mode never occurred in lone laser welding and, consequently, full penetration was not obtained even at the maximum laser power (2 kW) and minimum welding speed (500 mm/min). The capabilities of the hybrid laser-arc welding were investigated by two strategies: (1) low laser power with high arc energy and (2) high laser power with low arc energy. The macrosection, microhardness profile and microstructure of the welds were studied and the results were systematically compared. This made it possible to choose the best one for hybrid welding of AA2198 sheets among the investigated conditions.

2-Material and Experiments

AA2198 aluminum alloy plates with thickness of 3 mm were used in this study. The chemical composition of the material, which is the average of three X-ray fluorescence (XRF) measurements, is presented in Table 1.

Table 1. Chemical composition of AA2198 aluminum alloy (wt %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Li	Ag	Al
0.08	0.10	3.50	0.5	0.80	0.05	0.35	0.18	1.10	0.5	Balance

Before welding, oxides were removed from the surface of the base metal by steel wire brush. In addition, residue and grease were eliminated using acetone to achieve better welding quality.

In the experiments, linear bead-on-plate welds were made by using a continuous wave Nd:YAG laser source (HAASHL2006 D), with a maximum power of 2000 W, combined with a TIG welding source, with a maximum arc current of 350 A.

A schematic drawing of the hybrid laser-TIG welding process used in this research is depicted in Figure 1. As shown in this figure, the TIG torch is positioned prior to the laser along the welding direction, called laser-leading configuration.

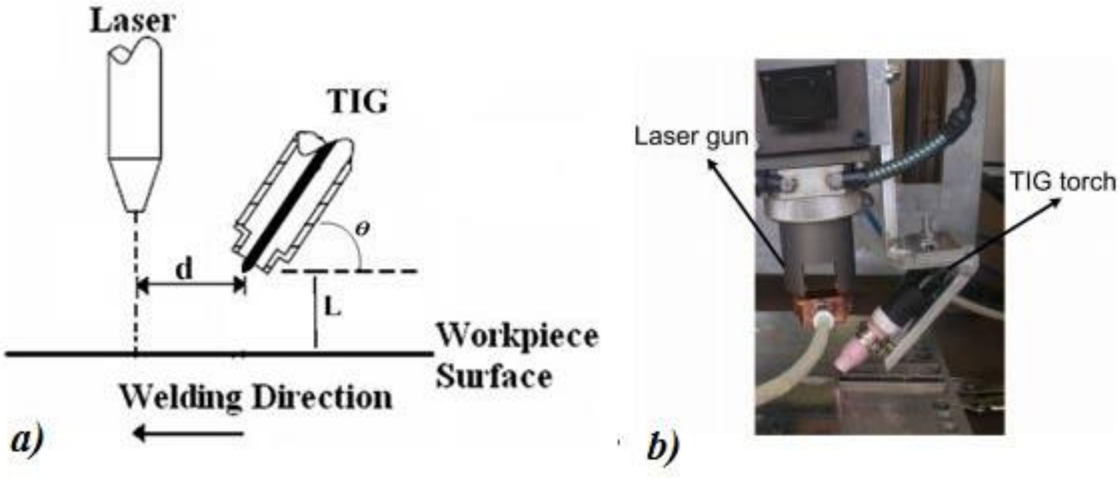

Fig.1 a) Schematic depiction of the laser and TIG torch positions. b) Experimental set up

HLAW has so many variable parameters that complicate adjustment of process parameters. In order to choose the most important welding parameters, some pre-tests were conducted. Some bead-on-plate welding tests were performed by varying the process parameters to determine the most effective parameters. Laser power (PL), welding speed (S) and arc current (A) were chosen as three most important parameters and other welding parameters were kept fixed during experiments.

Relative distance of laser action point to the electrode tip (d), and electrode distance from workpiece surface (L) were set at 2 mm in all experiments. The TIG torch is placed with a 45-degree angle to the horizontal surface and, consequently, both the laser spot and arc root are located at the same point.

The diameter of the tungsten electrode was 3.2 mm. During the experiments, pure helium was used as a shielding gas flowing from the TIG nozzle with gas flow rate of 20 Nl/min. The laser focal point was positioned on the surface of the workpiece. The spot diameter of the laser beam was about 0.5 mm.

Several experiments were carried out according to Table 2 to compare laser welding and hybrid laser-TIG welding. For laser welding, three welding speed levels (500, 800 and 1000 mm/min) were tested at the constant maximum laser power (2000 W). The arc voltage in hybrid welding is about 16 V for a 150-A arc and 17.18 V for a 180-A arc.

In hybrid welding, two strategies were examined: (1) low laser power with high arc energy, and (2) high laser power with low arc energy. In the first strategy, low laser power (P_L=100 W) was applied with two welding speeds (S) and three welding current (I) levels, as shown in Table 2. In the second strategy, the experiments were carried out at the maximum laser power (P_L=2000 W) with three different levels of the welding speed (S) and arc current (I) according to Table 2.

Table 2. Experimental setting

	Test No.	Laser power, P_L (W)	Welding speed, S (mm/min)	Arc current, I (A)
Lone laser welding	1	2000	1000	-
	2	2000	800	-
	3	2000	500	-
Hybrid welding with low laser power and high arc current	4	100	500	120
	5	100	800	120
	6	100	500	150
	7	100	800	150
	8	100	500	180
	9	100	800	180
Hybrid welding with high laser power and low arc current	10	2000	800	120
	11	2000	1000	120
	12	2000	1500	120
	13	2000	800	100
	14	2000	1000	100
	15	2000	1500	100
	16	2000	800	75
	17	2000	1000	75
	18	2000	1500	75

Each welded sample was sectioned from the middle of the weld line. The cut specimens were mounted in a phenolic thermosetting resin, conventionally grounded, polished and etched in the Keller's reagent. The microstructure was studied by optical microscopy (OM). Microhardness measurements were performed along a line 1 mm below the top surface on the transverse cross section of the weld using a micro indentation tester (CSM Instruments, Switzerland). The measurements were taken according to ASTM E384, by using a maximum load of 200mN and a dwell time of 10 s. Microhardness tests were repeated at least three times for each sample. The hardness profiles along the line from the middle of weld metal to the base metal were plotted.

3- Results and Discussion

Laser welding and hybrid laser-TIG welding were systematically compared with the aim of achieving full penetration in the -3 mm- thick AA2198 aluminum plates. Results in terms of macrosection, microhardness profile and microstructure of the welding joints are illustrated in the following sections.

3.1 *Macrosection of welding joints*

Figure 2 shows the cross sections of the welded plates obtained by lone laser welding at the power P_L=2000 W. As shown in the figures, full penetration was not obtained because keyhole mode never occurred, even at the minimum welding speed S=500 mm/min. The reason of this issue is that the laser energy is mostly reflected from material surface during laser welding of A2198 alloys. In the other word, absorbed laser energy into the workpiece is too low so that the penetration depth is unchanged even by decreasing the welding speed. In addition, the lens of the laser head was damaged in low welding speed due to the high reflection of the investigated aluminum alloy.

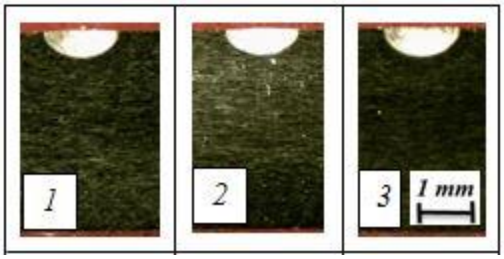

Figure 2. Cross sections (thickness t=3 mm) of the lone laser welding at the power P_L=2000 W for different values of the welding speed: 1) S= 1000 mm/min, 2) S= 800 mm/min and 3) S= 500 mm/min.

To achieve full welding penetration, laser-arc hybrid welding with low laser power was conducted. Figure 3 depicts the macrosection of hybrid welds where the laser power is set at 100

W and arc current (I) and welding speed (S) are varied from 120 A to 180 A and from 500 mm/min to 800 mm/min, respectively. The figure shows that the penetration depth in hybrid welding is significantly increased with respect to the lone laser welding even with a very low laser power (PL=100 W). In fact, as illustrated in Figure 3, full penetration was obtained in samples #6 and #8 (see Table 2). Consequently, due to lower current the lower heat input, sample #6 (PL=100 W, I=150 A and S=500 mm/min) is selected as the best candidate for hybrid welding with low laser power. In Sample #9 (PL=100 W, I=180 A and S=800 mm/min) as illustrated in Figure 3, fracture occurs which refers to the formation of shrinkage crack during the solidification of weld metal. High arc current (I) and degree of restraint could be the reasons for such a fracture crack [33].

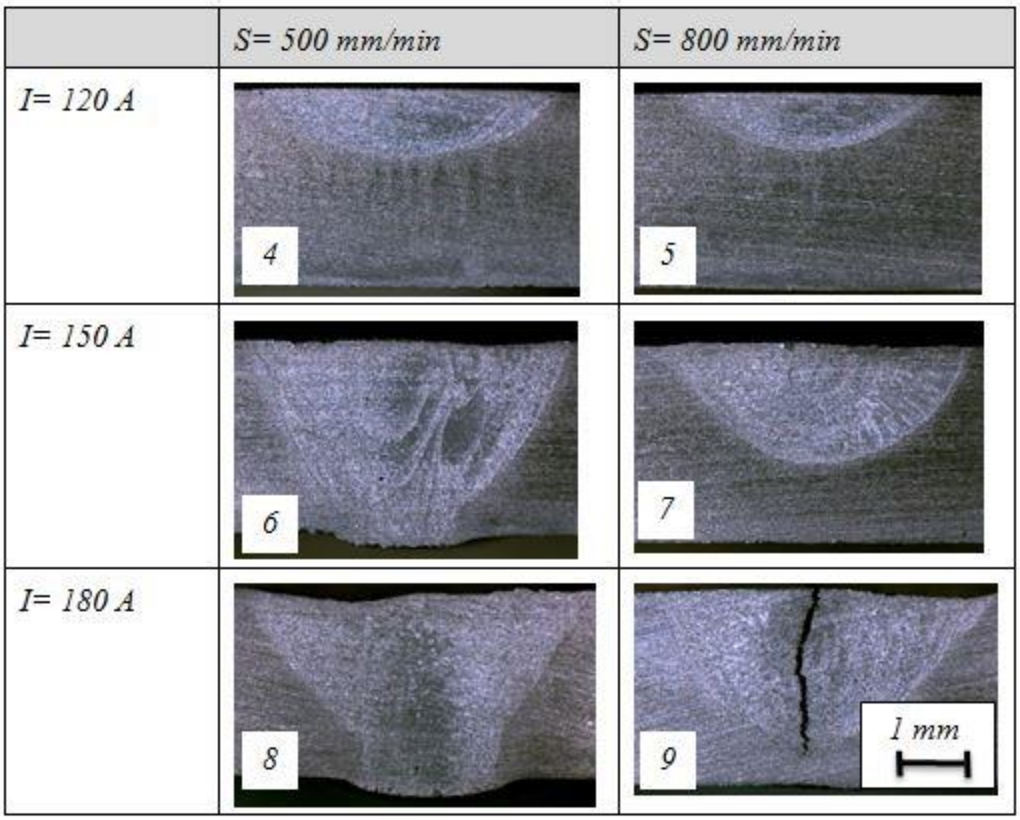

Figure 3. Cross section (thickness t=3 mm) of the hybrid laser-arc welds with low laser power (P_L=100 W) and different values of arc currents (I) and welding speeds (S).

The second approach of laser-arc hybrid welding process carried out in this research is welding with high laser power and low arc current. Figure 4 illustrates the macrosection of hybrid welds where the laser power is set at P_L=2000 W while arc current (I) and welding speed (S) are varied from 75 A to 120 A and from 800 mm/min to 1500 mm/min, respectively.

As shown in Figure 4, the penetration depth is larger with respect to the first approach. In addition, full penetration was achieved in samples #13 and #14. Although sample #13 (P_L=2000

W, I=100 A and S=800 mm/min) is full penetrated, because of the fracture in the weld zone ,it could not be selected as the best condition. This fracture is because of collapsing tendency of exorbitant full-penetrated weld pool. However, sample #14 is considered as the best combination (P_L=2000 W, I=100 A and S=1000 mm/min) due to higher welding speed and lower heat input.

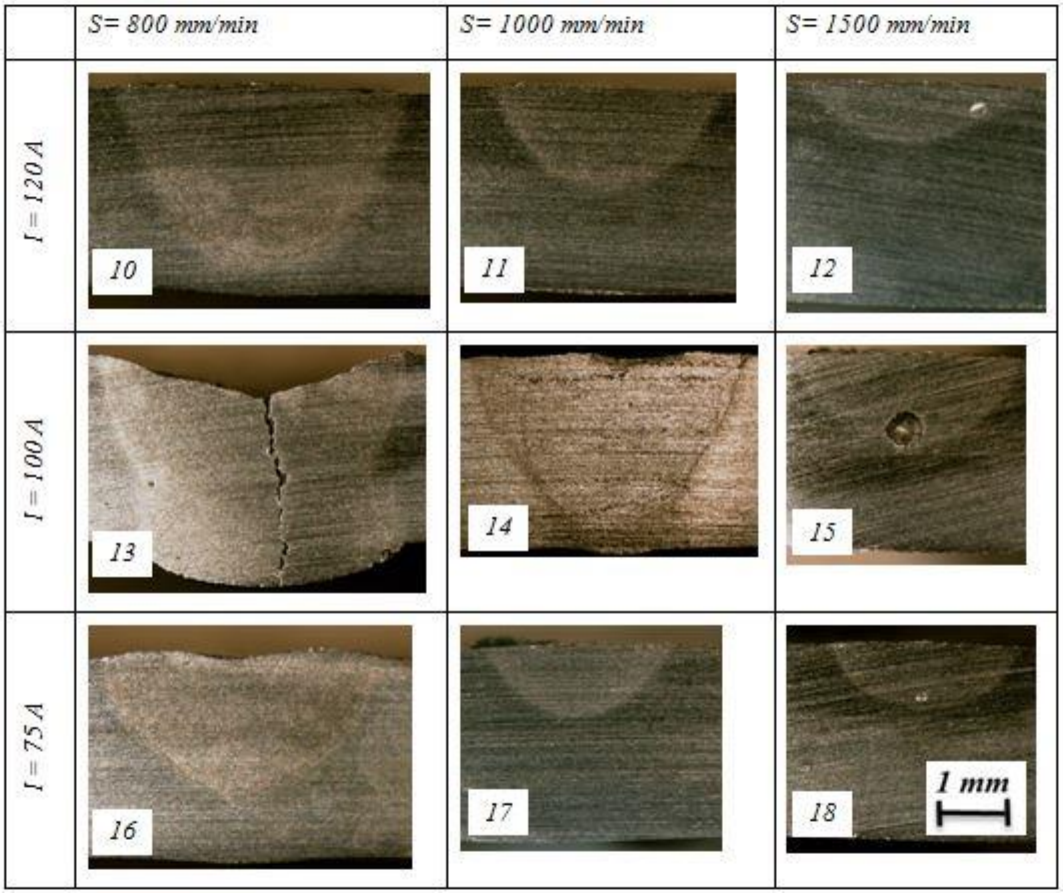

Figure 4. Cross section (thickness t=3 mm) of the hybrid laser-arc welds with high laser power (P_L=2000 W) and different values of arc currents (I) and welding speeds (S).

Another interesting fact in Fig. 4 is that by increasing the arc current from 100 A to 120 A, the weld depth is decreased. This trend is also reported by Chen and et. al. [34] for hybrid laser-TIG welding which is caused by keyhole effect of laser on arc. In another word, when the arc current increases, the arc plasma become wider which decreases the laser energy transferred to the weld pool and then the weld depth decreases (see samples #11 and #14). Therefore, there is an optimum range of the energy matching between laser and arc. In full penetration weld (see samples #13), crack appears in the weld metal because of the weld pool collapse.

Welding heat input is a very important parameter as it defines the weld geometry and properties and it can be adjusted by changing the welding parameters [35]. In this study, the heat input in hybrid laser-arc welding is calculated by Eq. 1 in order to compare heat input for two hybrid laser-arc approaches.

$$Q_{HLAW} = Q_{Arc} + Q_{Laser} \qquad (1)$$

where Q_{HLAW} is the heat input of HLAW (J/mm), Q_{Laser} and Q_{Arc} are the heat input (J/mm) of Laser and arc source (J/mm), respectively, and are given by the following equations:

$$Q_{Arc} = 60 \times V \times I / S \qquad (2)$$

$$Q_{Laser} = 60 \times P_L / S \qquad (3)$$

where V is the arc voltage (V), I is the arc current (A), S is the welding speed (mm/min) and P_L is the laser power (W).

According to Eq. 1, the value of the heat input for sample #6 (P_L=100 W, I=150 A, V=15.9 V and S=500 mm/min), which is the best candidate in HLAW with low laser power, is equal to 298.2 J/mm. Beside, the heat input for sample #14 (PL=2000 W, I=100 A, V=13.9 V and S=1000 mm/min), which is the best candidate in HLAW with high laser power, is equal to 203.4 J/mm.

Previous studies showed that there are several advantages in welding with lower heat input than higher heat input such as smaller weld pool size, smaller Heat Affected Zone (HAZ), better mechanical properties and less residual stress and [33, 35 - 38] even if mechanical properties of the joints are not analyzed in this investigation, based on the values of the heat input sample #14 is expected to provide better performance than sample #6. As a result, it can be concluded that ~~using~~ second approach (high laser power and low arc energy) is superior to the first approach (low laser power and high arc energy) in hybrid laser-arc welding of the AA2198 alloy.

3.2 Microstructure and microhardness of welding joints

The micro-hardness and HAZ microstructures of the two samples with full penetration (#6 and #14) are studied in this section. The microhardness tests were conducted on the transverse cross-section of the welds along a line 1 mm below the weld surface.

Figure 5 shows the micro-hardness and HAZ microstructure for the HLAW joint with lower heat input (sample #14). The hardness of the base metal is around 105 HV; while the microhardness of the weld zone reduces to a minimum value of 65 HV, around 62% of the base material. It can be seen that in the HAZ, the microhardness increases from value of the weld zone to that of the base metal. As illustrated in Figure 5 (a) the width of the HAZ is about 300 µm confirmed by Figure 5 (b). Similar considerations can be applied to Fig. 6, which shows the micro-hardness and HAZ microstructure for the HLAW joint with higher heat input (sample #6). Even if there is not significant variation in the microhardness of the weld zone with respect to sample #14, Figures 6 (a) and 6 (b) clearly show that the width of the HAZ for sample #6 (around 1000 µm) is much higher than that of sample #14. These results are in agreement with the heat input values calculated in section 3.1.

As seen in Figures 5 and 6, weld metal has a dendritic microstructure and HAZ has a columnar microstructure which is caused by epitaxial growth from weld pool boundary. In addition, a very narrow zone with equiaxed grains is seen between the weld metal and HAZ as reported by D. K. and J. P. Dean [39] for the TIG welding of Al-Cu-Li alloys.

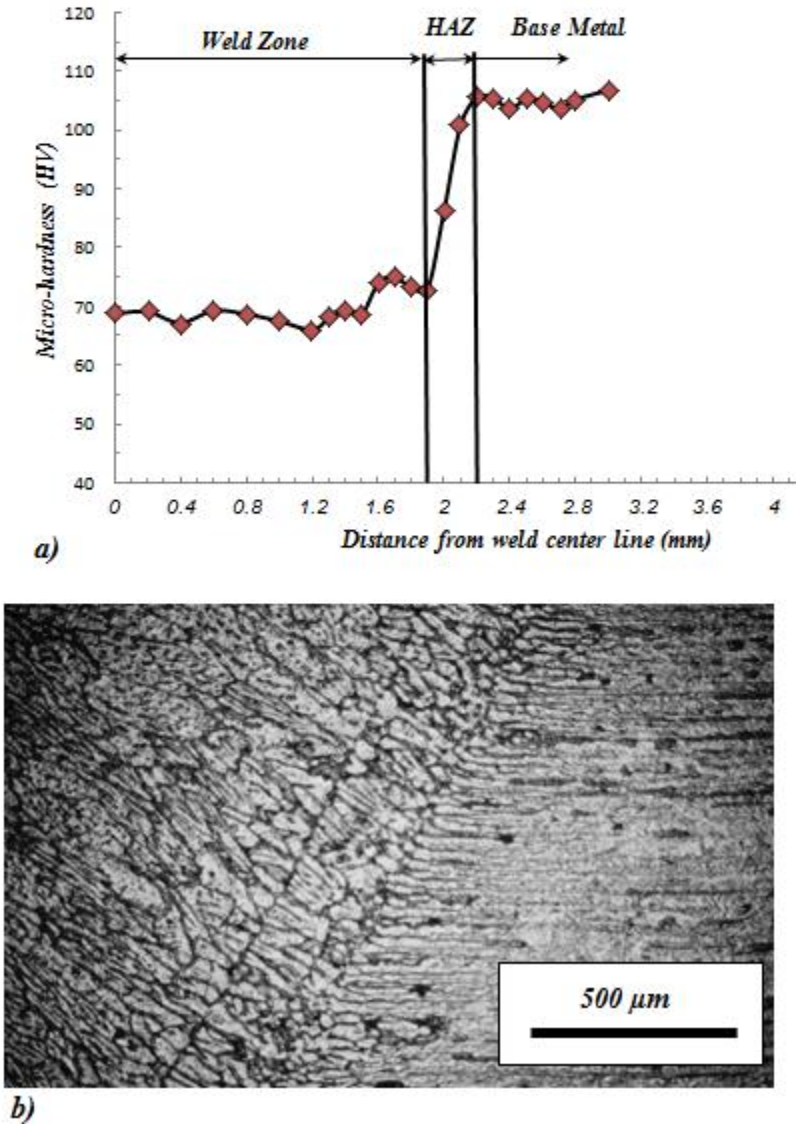

Figure 5. Micro-hardness and HAZ microstructure across hybrid laser-arc joint with low heat input (sample #14): a) micro-hardness profiles of joint b) HAZ cross section microstructure of weld.

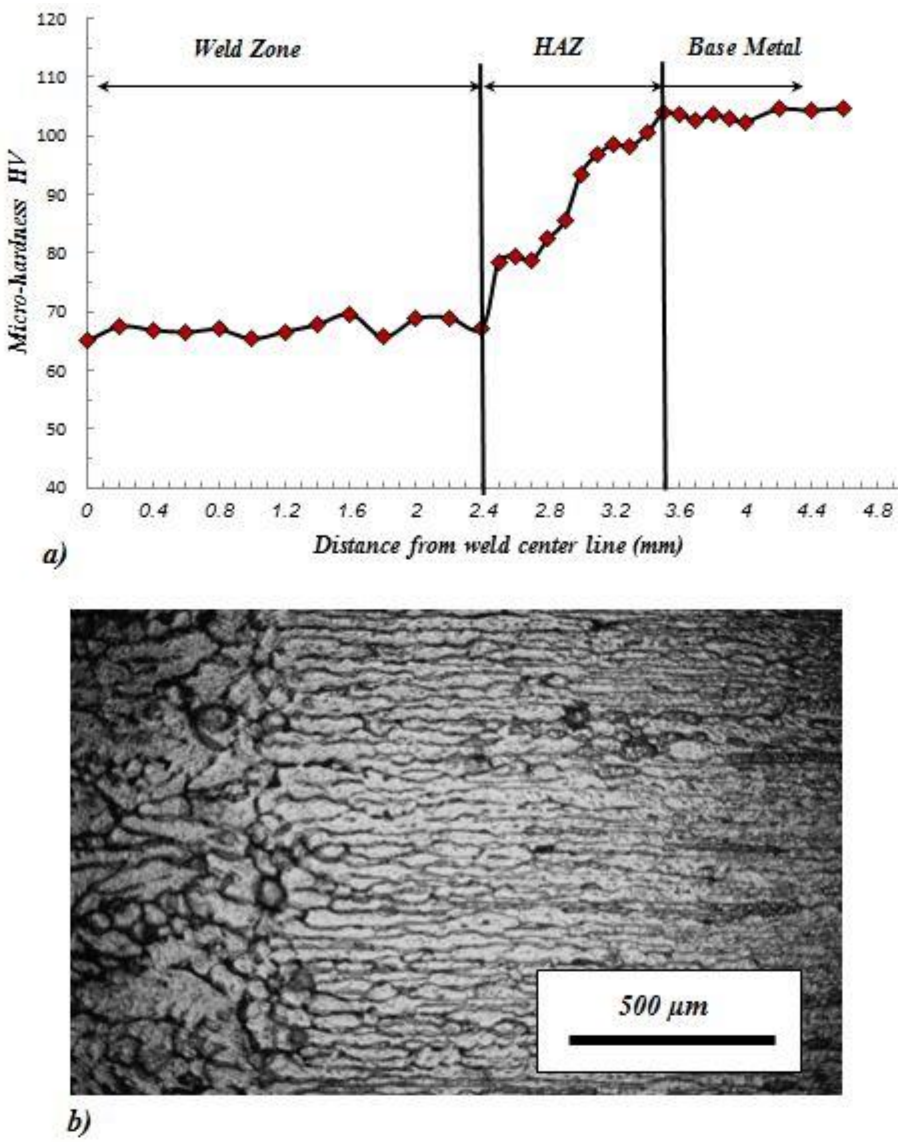

Figure 6. Micro-hardness and HAZ microstructure across hybrid laser-arc joint with low heat input (sample #6): a) micro-hardness profiles of joint b) HAZ cross section microstructure of weld.

4. Conclusions

The main aim of this research is to study the capability of the hybrid Nd:YAG welding compared to lone Nd:YAG laser welding in AA2198 aluminum alloy plate with thickness of 3 mm. Two strategies of hybrid welding have been analyzed: 1) low laser power combined with high arc energy and 2) high laser power with low arc energy. The following conclusions can be drawn:

1. Full penetration never occurs in lone laser welding even at the maximum laser power (2000 W) and low welding speed (500 mm/min). In fact, welding is performed in

conduction mode and keyhole mode is not formed due to the high thermal conductivity and laser radiation reflection of the alloy.

2. The cross-sectional shape of hybrid laser-arc welds showed that change of the welding mode from conduction to keyhole can be obtained even at high welding speed (1000 mm/min). This issue can prove the high capability of hybrid Nd:YAG laser-TIG welding compared to lone Nd:YAG laser welding for AA2198 aluminum alloy. The main reason is probably the synergic effects between arc and laser heat sources which results in increasing melting efficiency during welding. In another word, laser and arc sources help each other to have higher energy efficiency and thus a deep weld pool is formed even in high welding speed.
3. The comparison of the micro-hardness profile and microstructure results of the two hybrid welding strategies showed that the second approach (high laser power with low arc energy) is superior to the first approach (low laser power with high arc energy) for hybrid Nd:YAG laser-TIG welding of AA2198 alloy with the thickness of 3 mm. The reason is the lower heat input and HAZ width in second approach compared to the first one.
4. The best setting for HLAW process of AA2198 alloy with the thickness of 3 mm satisfying the desired weld of full penetration was achieved at laser power of 2000 W, arc current of 100 A and welding speed of 1000 mm/min. The heat input for this situation was calculated to be 203.4 J/mm.

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