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Welding Characteristic Analysis of Hybrid Welding on 2014 Aluminum Alloy

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The experiment of TIG arc and laser high-frequency pulse TIG hybrid welding for 2014 aluminum alloy with the thickness of 7mm were carried out. Through the two welding processes experiments, the correlation between welding process and joints structure as well as performance was studied. The result show that compared with the TIG welding, laser-assisted TIG compound welding and laser high-frequency pulse TIG compound welding increase welding speed, reduce heat input significantly, refine the welding structure, and reduce the width of Eutectic α(Al)+θ (CuAl2) structure of crystal boundary, especially effectively eliminate the blowhole defect of welding fusion zone, Furthermore, the joint properties and stress corrosion resistance both are improved significantly. The average fracture time for 2014 aluminum alloy through the laser high-frequency pulse TIG hybrid welding is significantly longer than that through the TIG welding, which is about 93% of the average fracture time for 2014 base material.

Keywords: aluminum alloy; hybrid welding; joint properties

1. INTRODUCTION

Al-Cu alloy is characteristic of small specific weight, high specific strength and specific stiffness, being easy to process with good physical and chemical properties [1], so it is widely applied to the aerospace industry which demands an extremely high weight and strength of structural components. In current welding process, variable polarity filler rod TIG argon arc welding is largely used, which easily leads to blowholes and cracks in welding with low joints' strength and welding efficiency. Therefore, new welding process needs exploring to reduce the metallurgical defects in welding line, improves and increases the comprehensive performance of Al-Cu alloy welding joints.

Generally, a welded material is composed of three zones with different corrosion behaviours: base zone(BZ), heat-affected zone(HAZ) and weld zone(WZ). The heat affected zone next to the welding can be more likely attacked due to the metallurgical changes caused by heating cycles. It can become more sensitive to corrosion as a consequence of the precipitation of chromium carbides in the HAZ[2,3], which is of important concern in the technology of corrosion[4].

Laser arc compound welding appeared in late 1970s, which can be classified into two kinds based on the dominant heat source: one is arc -assisted laser welding which is generally considered to be laser-arc compound welding. It can reduce blowholes, cracks, undercuts and other defects when compared with laser welding, as well as improve the structural performance and stress condition of welding line and heat-affected zone [5-10]. The other is laser-assisted arc welding, in which arc energy dominates. Generally, low-power laser-assisted arc which will not form anatexis “small holes” is employed. Compared with arc welding, the addition of laser benefits the concentration of arc energy and helps increase the stability of welding process, avoiding arc drift at a high welding speed and thus giving a rise to the welding quality [11-14].

Recent years, there have been some initial researches on the addition of high-frequency pulse current during the aluminum alloy variable polarity TIG welding process. The results demonstrate that high-frequency pulse current （≥10kHz） significantly refines the solidification structure of aluminum alloy, helping increase and improve the structure and performance of aluminum alloy welding joints [15-17].

TIG arc-assisted laser welding test of early stage Al-Cu shows that TIG arc-assisted laser compound welding can markedly increase welding speed, reduce heat input, refine welding structure, decrease the width of eutectic structure of the grain boundary as well as the width of fusion area and heat-affected zone when compared with filler rod TIG welding. However, due to the great temperature gradient, quick molten pool cooling and uneven welding zone’s grains and orientation, micro blowholes are easily seen in welding joints, causing low welding joints’ elongation and stress corrosion resistance. Accordingly, filler rod TIG welding, laser-assisted arc TIG compound welding, laser-high frequency pulse TIG compound welding are used together to conduct butt welding test to 6mm-thick 2014 aluminum alloy. By testing and analyzing the joints’ mechanical properties, Stress corrosion resistance and metallographic structure, the relation of 2014 aluminum alloy welding joints’ structure, performance and welding process is investigated.

2. TESTING DEVICES AND METHODS

2.1 Testing devices

The welding system of compound heat source is shown as figure 1. Laser-assisted TIG compound welding system employs 1000W semiconductor laser developed by Laser Institute of Beijing University of Technology and TETRIX521 TIG welder of EWM to set up the platform of welding test. During the test, the defocusing amount of laser is 0mm, and 75 º as the included angle of laser beam and horizontal plane, 4mm of the distance between tungsten electrode and work piece and

4mm between tungsten electrode and laser beam, while the included angle of welding torch and horizontal plane is 70 º. In laser-high frequency pulse TIG compound welding test, the welding power source which is specific for composite pulse current was parallel connected with EWM Variable polarity power source and the pulse amplitude of pulse welding power source was 50 A, while the pulse frequency was 20kHz.

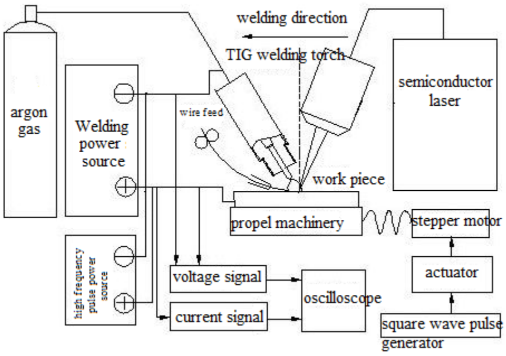


Figure 1. Schematic diagram of hybrid welding

2.2 Test method

Al-Cu alloy used in the test is 2014 aluminum alloy, while the size of welding test piece is 150mm×150mm and 6mm thick. Y-shape groove is used, leaving a truncated edge ≤3mm. The welding process is single-sided single-layer welding and the welding filler rod is Φ1.6mm ER2319 welding wire. Use welding wire of alloy content higher than the parent metal as fill material, It is usually possible to prevent weld cracks, The composition of the materials of the 2014 aluminum alloy and the chemical composition of the welding wire of ER2319 are shown in Table 1, Table 2.

Table 1. The composition of aluminum alloy 2014

Cu	Mn	Mg	Si	Fe	Ti	Zr	V
4.2	0.8	0.5	0.75	0.7	0.15	—	—

Table 2. Chemical composition of the welding wire ER2319

Si	Fe	Cu	Mn	Ti	Al
4.7	0.30	2.3	≤0.05	0.25	Margin

Before welding, the welding test pieces and welding wires were cleaned with acetone to remove surface oil, and the oxide film was removed by cleaning the surface with wire brush. The tungsten electrode was made of cerium, with a diameter of 4.8mm. The protective gas was high purity argon with a flow rate of 12L/min. as shown in Figure 3,use special AC current TIG arc (being direct current at impulse peak and square wave AC at pulse base stage) to weld, helps to reduce heat input and removal of the oxide film during the welding process[18]. Laser-high frequency pulse TIG compound welding test used 500W laser and special AC TIG arc to weld test pieces. During welding process, the composition of high frequency pulse current was conducted during direct current electrode negative (DCEN). The welding parameters of filler rod TIG, laser-assisted TIG compound welding and laser-high frequency pulse TIG compound welding are shown in table 3.In filler rod TIG welding, due to the Y-shape groove and disperse TIG arc energy, a relative low welding speed of filler rod TIG welding was used to avoid the discontinuous weld formation caused by TIG arc shaking. When employing 500 W laser-high frequency pulse TIG compound welding, due to the addition of laser, the stability of TIG increases greatly, so a higher speed was chosen.

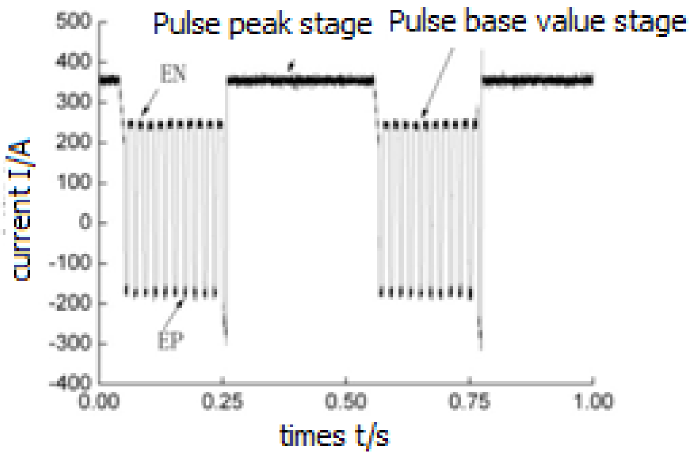


Figure 2. Special AC TIG arc

After welding, OLYMPUS laser confocal scanning microscope was used to observe and analyze the welding structure, while TH-8110S servo-type electronic universal testing machine was taken to test the mechanical properties of weld joints. The tests of stress corrosion employed slow strain rate which was set as 10^{-4} mm/s.

Table 3. welding parameters

technological parameter	filler rod TIG	laser-high frequency pulse TIG
welding speed v/（m/min）	0.15	0.3
Laser power P/(W)	—	500
pulse peak time t/s	0.15	0.15
pulse peak current I_t/A	350	405
pulse base value time t/s	0.15	0.15
pulse base value EN phase’s current I_{EN}/A	240	275
pulse base value EP phase’s current I_{EP}/A	240	275
pulse base value AC frequency f_1/Hz	50	50
High - frequency pulse frequency f_2/kHz	—	20
High - frequency pulse current I_h/A	—	50

3. TEST RESULTS AND DISCUSSIONS

3.1 TIG arc power contrast

The current and voltage signal are collection during the welding process of Wire filling TIG arc welding and laser-high frequency pulse TIG compound welding. Found that the TIG arc pulse peak current and a pulse base current are maintained at the same numerical value during the process of the two welding when Voltage there is a greater change. TIG arc between two poles of laser-high frequency pulse TIG compound welding , the voltage has a clear decline in characteristics, voltage is reduced from about 14V to 8V during the pulse peak, the EN period of the pulse-base stage that voltage is reduced from about 12V to 5V, the voltage did not change significantly in the EP period about 17V. From wire filling TIG arc welding TIG arc power chart (FIG. 4) and laser-high frequency pulse TIG compound welding TIG arc chart (FIG. 5) can be seen: relative to the wire filling TIG arc welding, laser-high frequency pulse TIG compound welding TIG arc power-time chart has significantly changed, arc power from 4.9 kW dropped to 2.8 kW in pulse peak stage, the EN period of the pulse-base stage that power is reduced from about 2.9W to 1.2W, the power did not change significantly in the EP period about 2.9W.

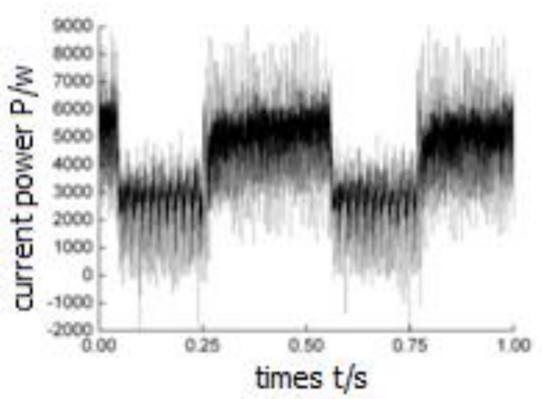


Figure 3. TIG arc power

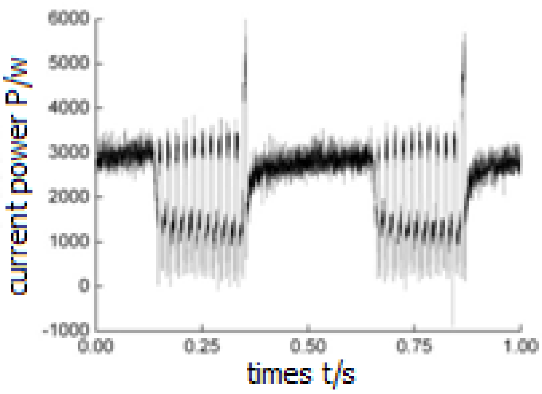
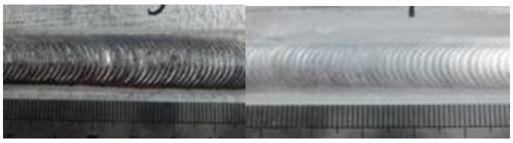


Figure 4. laser high-frequency pulse TIG arc power

3.2 Comparison of the weld shape

laser-high frequency pulse TIG compound welding surface morphology as shown in Figure 6, Weld surface is bright, white, uniform penetration, no significant surface defects, and there are beautiful " fish-scale pattern " appeared, more uniform scale pattern show welding process is very stable, through X ray flaw detection, did not find many big pores and inclusions phenomenon. Compared with the filler wire TIG arc welding process, a positive weld width decreased, And more uniform scale pattern formation, This is primarily attributed to the change of the arc power, after laser joined the arc, The power of the arc dropped 2.1kW during the pulse peak, although the EN period of the pulse-base stage the power also dropped 1.7kW, but in the pulse base EP period that the power of the arc does not reduce, because of EP period not only has the role of clean up the oxide film, but also transport heat to the molten pool, the heat input no less than the EN period, so caused heat input quantity difference decreases of the pulse peak stage and pulse base value stage , and reflected in weld morphology is laser-high frequency pulse TIG compound welding fusion width diminishing, uniform scale pattern formation.

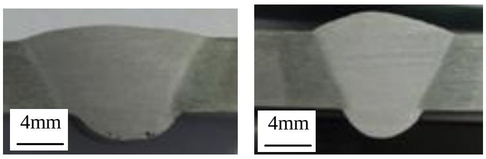


a)filler rod TIG b)laser high-frequency pulse TIG arc

Figure 5. Surface appearance of TIG process and Laser- assisted TIG process

3.3 The analysis of joints' features

The welding sectional morphologies of 2014 aluminum alloy's three welding processes are shown as figure 2. The heat input of filler rod TIG welding is 1.6kJ/mm, and the welding line has a positive weld width of 16.1mm and back weld width of 9.5mm. The heat input of laser-high frequency pulse TIG compound welding is 0.9kJ/mm, and the welding line has a positive weld width of 12.0 mm and back weld width of 5.5mm.



a)filler rod TIG b)laser high-frequency pulse TIG arc

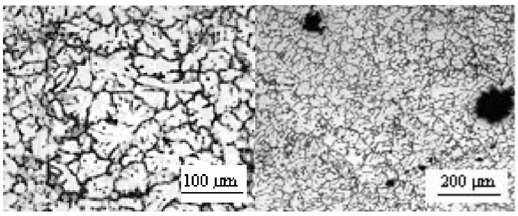
Figure 6. Cross-section shape of weld by two welding processes

The microstructures of weld zone's center of different welding process are shown in figure 3, where the crystals are isometric, and the welding structure takes α(Al) solid solution as matrix in which there are a lot of θ (CuAl2) with small particles functioning strengthening the matrix. Between the matrix grain boundary and fern-leaf crystal, there are plenty of α(Al)+θ (CuAl2) eutectic phase, which distributes in continuous network-like way.

two kind of welding process, filler rod TIG weld zone has the larger structural grain and the greater width of eutectic phase and relatively few content of solute in crystals. laser-high frequency pulse TIG compound welding have smaller structural grains in weld zone center than filler rod TIG welding does; besides, their eutectic phase width significantly reduces, and the content of solute in crystal increases, which is mainly caused by the different speeds of welding process and heat input amount. according to the solute elements segregation formula of weld

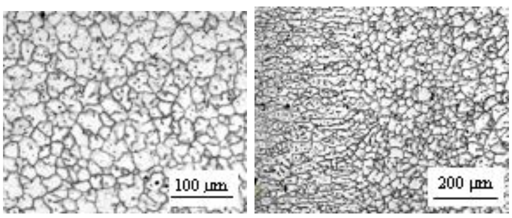
$$C_s=K_0C_0(1-g)^{K_0-1}$$

Where C_S is the content of the solute elements in the coagulum, K_0 is the equilibrium distribution coefficient of Cu, C_0 is the content of alloy starting solute elements, g is the percentage of the solidification metal. In the welding process, the content of the solute elements is increased with the increase of the undercooling. laser-high frequency pulse TIG compound welding has a welding speed, few welding heat input, short residence of high temperature of molten pool of metal, high cooling speed, large supercooling degree of forefront of dendrite and a high content of solute elements; therefore, their solute element content in matrix is higher than that of filler rod TIG welding, but there is lower eutectic phase width of crystal boundary.



weld zone fusion zone

(a) TIG welding with filler wire



weld zone fusion zone

(b) laser assisted TIG hybrid welding

Figure 7. Microstructure of weld zone and fusion zone

In the welding of 2014 aluminum alloy, blowhole is the most commonly seen welding defect. As seen from the figure 3 of the microstructure of weld fusion, the morphologies of fusion zone is uneven. The microstructures of filler rod TIG welding and laser-assisted TIG compound welding are columnar dendrites and cellular dendrites, separately. There is an apparent and small isometric crystal zone in the fusion zones of laser-high frequency pulse TIG compound welding, of which the crystal morphology is similar to that of welding center.

There is crystalline layer hole in filler rod TIG weld fusion zone with a size between 50～100μm, but not significant blowhole in the weld fusion zones of laser-high frequency pulse TIG compound welding. It can be inferred that the combined use of the two heat sources' welding process can effectively reduces and even eliminates weld blowhole defect. In filler TIG welding, arc is used for blowhole which is largely discharged by the vibration of low-frequency modulation pulse, while blowhole in pool edge cannot be discharged without enough vibration. After adding laser and high-frequency pulse, the arc gets an increased stiffness and larger impact force, leading to the regular circular flow of liquid metal in melting pool to discharge the blowhole in pool edge, effectively promotes the blowhole at pool edge to liberate. The appearance of small isometric crystal zone in weld fusion zone of laser-high frequency pulse TIG compound welding demonstrates that 20KHz high frequency pulse energy can refine weld particles. When high frequency pulse acts in weld pool, the high frequency vibration can break the initial dendritic structure on solid-liquid interface and increase crystallization center, as well as draw in the unmelted A13Zr with a high melting point, forming nucleation and promoting small isometric crystal zone to take shape.

3.4 Microhardness curve

The hardness diagram of welded joints by different welding processes is shown as figure 4, and their hardness of weld zone is all about 85HV. The weld fusion zone of filler rod TIG welded joints significantly softens, and the lowest hardness of fusion zone is only 68HV. The joints using laser-high frequency pulse TIG compound welding processes do not significantly soften in this area. Accordingly, compound heat source joints have a slightly higher hardness than filler TIG welding joints does, and hardness value does not change as dramatically as that of filler rod TIG welding joints.

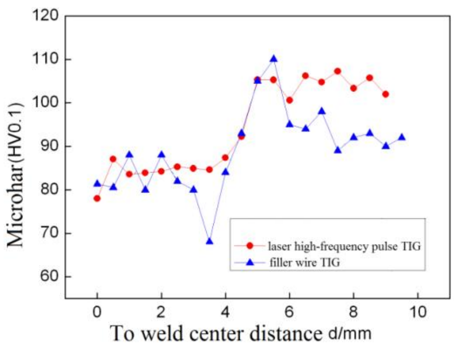


Figure 8. Hardness diagram of welded joints by different welding processes

3.5 The joint tensile mechanical properties and fracture SEM morphology

The fracture position of filler rod TIG welded joints is in weld fusion zone, while laser-high frequency pulse TIG compound welded heat source process' welded joints are in the heat-affected zone of the welding line which is close to base material side. Figure 5 is about the fracture roads of welded joints. It can be seen that filler rod TIG welded joints fracture along the eutectic phase of crystal boundary during tensile process. In crystal boundary, $\alpha+\theta$ eutectic structure is brittle structure. The content and distribution of network-like eutectic structure determines the tensile property of welded joints, and the laser-high frequency pulse TIG compound welded joints manifest transgranular fracture in tensile process.

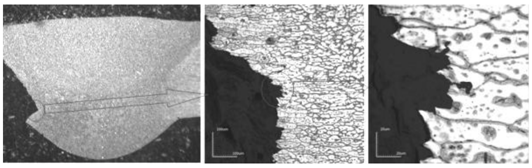


Figure 9. Fracture roads of laser high-frequency pulse TIG arc

The tensile properties of 2014 aluminum alloy base metal and joints welded by different welding processes are shown in table 2. Welded joints' tensile strength and elongation are obviously lower than those of base metal. The severity factor of filler rod TIG welded joints is only 0.58, and its elongation rate is only the 26.1% of base metal. There is no significant plastic deformation in joints tensile fracture but blowhole in fracture section. The blowhole will not only reduce the effective bearing area of welded line, but also form stress concentration, decreasing welding line's strength and plasticity.

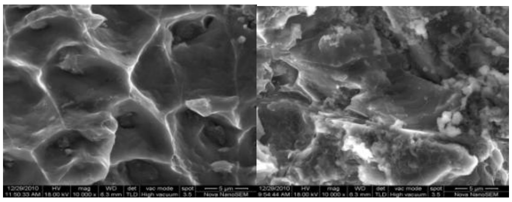
The welding process alters the microstructure of the materials, causing local variations in the composition and structure of the material. These changes increase the dissimilarity of the base/weld pair and can cause galvanic corrosion[19]. Previous works[20-23] has shown that corrosion is more severe in the contact region between the base and the welded zones. This is mainly due to the galvanic corrosion between the base and the welded metal.

Compared with filler TIG welded joints, the laser-high frequency pulse TIG compound welded joints have remarkably increased property, and the tensile strength has been increased by 8%, reaching 62.5% of that of base metal, while the elongation rates has been increased by 17%, being 30.4% of base metal. The increase of tensile strength and elongation is primarily caused by the decrease of heat input. On the base of small power laser, this welding process, with the added high frequency pulse energy, functions the high-frequency vibration of melt pool, further refines welding structure, and thus the welding line's mechanical properties increases. Filler wire TIG welding joint tensile fracture morphology shown in Figure 9 (a), Fracture is mainly composed of coarse transgranular cleavage plane, dimple a little, Performance for "toughness + brittle" mixed fracture when the brittle fracture is given primary.

The laser-high frequency pulse TIG compound welded joint tensile fracture morphology shown in Figure 9 (b) ,a large number of dimples on the fracture, present microporous coalescence fracture, belongs to the ductile fracture, and similar pien brightness larger at the edge of the dimple, a second phase particle exists in the brightness darker flat bottom, This is because the substrate interface and the second phase particles cleaving forming the cracks (dimple) source when the sample in the tensile deformation., The dimple gradually rive with the increase of stress and deformation increases. Larger protuberance tear ridge is formed around dimple. From above, the fracture pattern analysis and tensile test results are consistent, the laser-high frequency pulse TIG compound welded joints have better mechanical properties than the filler wire TIG welding joints in 2014 aluminum alloy.

Table 4. Tensile properties of welded joints and base metal

Welding process	*Tensilbe strength* σ_b/MPa	Elongation, δ_5 (%)
Filler rod TIG	255	3.0
Laser high-frequency pulse TIG	287	4.0
2014 base metal	441	11.5



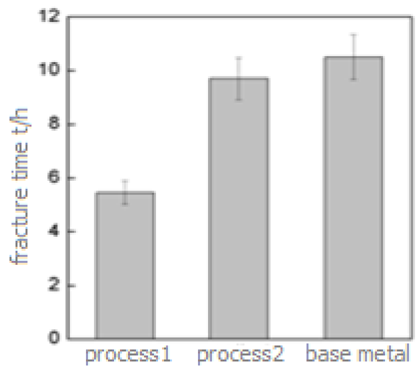
a)filler rod TIG b)laser high-frequency pulse TIG arc

Figure 10. SEM fractography of SSRT specimens

3.6 The resistance to stress corrosion of joints

In the test of 2014 base metal and the two welding processes' joints' resistance to stress corrosion, slow strain rate test (SSRT) is used, which is conducted in the NaCl solution with 3.5% of etching solution at 25℃. The fracture time of the specimens for SSRT of stress corrosion is in figure 6. Fracture time refers to the time from the start of SSRT to specimens' fracture, being the most important indicator of evaluating cracking sensitivity. The fracture time of 2014 base metal is 10.55h, whose tensile specimens have significant constriction, and the resistance to stress corrosion is markedly higher than that of welded joints.

Filler rod TIG welded joints' tensile specimens manifest remarkable brittle fracture, and there is blowhole in the fracture position of joints' stress corrosion, providing favorable pathway for corrosion cracks. Besides, theα(Al)+θ ($CuAl_2$) eutectic structure which is extensively existed in crystal boundary increases the pathways of stress corrosion cracks along crystal boundary, and the cracking sensibility of joints. Therefore, the resistance to stress corrosion of filler rod TIG welded joints is not great, with a fracture time of 5.45h. The stress corrosion crack (SCC) of laser-high frequency pulse TIG compound welding joints happens in materials' yield deformation. The tensile specimens have constriction, which is ductile fracture. Compared with filler rod TIG welded joints, the fracture time increases by 78%, being the 93% of base metals, while the resistance of stress corrosion performance is significantly increased, due to the growth of welding speed, the reduce of heat input and eutectic structure width and blowholes and grain refinement caused by the vibration of high frequency energy to melting pool. In addition, low heat input also reduces atoms precipitate free zone (PFZ) near weld junction, and PFZ is one of the zones where stress corrosion cracks most likely happen.



(Process1- filler rod TIG welding, process 2- laser high-frequency pulse TIG welding)

Figure 11. Time-to-failure of specimens

The electrochemical results show that the welding process shifts corrosion potential to more cathodic values. The corrosion and the passivation current densities increase as a consequence of welding, involving a decrease in corrosion resistance[24-26]. This phenomenon is accentuated at higher temperatures. Moreover, the polarization curves have shown the absence of hysteresis loop, a characteristic phenomenon of general corrosion processes in the tested medium.

4. CONCLUSION

The use of laser-high frequency pulse TIG compound frequency in 2014 aluminum alloy welding, compared with filler rod TIG welding, can significantly increase welding speed, reduce heat input, refine welding structure, decrease eutectic structure width of the grain boundary, effectively reduce and even remove the blowhole in weld fusion zone.

Laser-high frequency pulse TIG compound welding can improve and increase the mechanical properties and the resistance to stress corrosion of 2014 aluminum alloy welded joints. Compared with filler rod TIG welding, the compound heat source welded joints SCC fracture time remarkably increases, reaching 93% of base metals.

Laser-high frequency pulse TIG compound welding can improve the mechanical properties of welded joints of 2014 aluminum alloy, compared with wire filling TIG welding, tensile strength increased by 11.2%, the elongation of after fracture increased by14.3%. The SEM morphology of laser auxiliary TIG arc compound welding welding joint fracture show large number of dimples existing the welding joint fracture ,it belong to the ductile fracture. Microstructure variations caused by welding convert the weld zone into the anode of the galvanic pair formed with the base zone of the materials; although the galvanic effect between base Alloy 2014 and the weld zone is hardly significant in the studied conditions. Consequently, Alloy 2014 can be used as a structural material in the industrial equipment of phosphoric acid plants.

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