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Original Article

Mechanical properties of repair welds for aluminum alloy 6082-T6 by pulsed MIG welding process♣

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Abstract

The mechanical properties of repair welding of aluminum alloy 6082-T6 welded with 5356 filler metal were studied using pulsed metal inert gas (MIG) welding process at frequencies of 1.5 Hz and 5 Hz. The effect of pulse current frequencies on their mechanical properties of welded samples was investigated by analyzing macrostructure, microstructure, the density of porosity, and mechanical tests such as tensile, bending and hardness tests. Experimental results showed that repeated heat input and porosity in weld metal contributed to poor mechanical resistance. It was found that increasing the frequency has a beneficial effect on reducing the amount of porosity as well as the size of pores in the welded samples, giving superior mechanical properties. The repair weld welded using high pulse current frequency provided higher tensile strength and superior bending resistance, suggesting that the high pulsed MIG welding is preferable for repair welding of Al 6082-T6.

Keywords: pulsed MIG welding, aluminum alloy 6082-T6, repair welds, porosity, mechanical properties

1. Introduction

Nowadays, aluminum alloys are extensively utilized in a variety of transportation industries such as rolling stocks, car bodies and shipbuilding for their attractive properties including lightweight, high strength, excellent corrosion resistance, good weldability and formability (Troeger & Starke, 2000). Among them, 6082-T6 aluminum alloy has ability to provide excellent mechanical properties because of the presence of heat-treatable $MgSi_2$ intermetallic phases (Totten & MacKenzie, 2003). It is well-known that MIG welding process is widely used for joining of the aluminum alloys (Leoni, Sandness, Grong, & Berto, 2019). With the increase of application areas it is unavoidable to join the structural parts (Huang *et al*., 2017). Conventional MIG welding repair causes problems like porosities in weld metal and lead to unacceptable mechanical properties of the joints (Imam Fauzi, Che jamil, Samad, & Muangjunburee, 2017). The possibility of pores formation is due to the high solubility of hydrogen gas in the molten aluminum, although the arc and the molten pool are protected from atmosphere by shielding gas (Praveen & Yarlagadda, 2005). This this drawback can be overcome using pulsed MIG welding process which can control metal transfer into the weld metal, reduce the heat cycle and had beneficial effect on reducing porosity (Praveen , Yarlagadda, & Kang 2005). Moreover, vibration of molten pool during pulse period can take out gas trapped in the weld metal. Therefore, pulsed MIG welding has been reported to be an excellent choice for welding of aluminum alloys (Kumar, Dilthey, Dwivedi, Sharma, & Ghosh, 2008).

The repair welding is often required for maintenance of poor welded structures with one or more welding defects. The main challenge faced by manufactures is to repair of aluminum alloys with equivalent quality compared with the original welds. The influence of the pulse current frequency on microstructure and mechanical properties of 2198 Al-Li alloy was studied using ER 4043 filler material for aerospace equipment (Wang, Suo, Wu, Wang, & Liang, 2018). Friction stir welding (FSW) was also used to investigate groove defect which deteriorated mechanical properties and microstructural characteristics of the repair welds (Liu & Zhang, 2009). Another investigation focused on

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weld quality of thin sheet welding of Al 6082 alloy produced by using pulsed GMAW (Kumar, Dilthey, Dwivedi, & Ghosh, 2009). However, there is lack of knowledge on the investigation of the welding repair of aluminum alloy rolling stocks by MIG welding using pulse current frequency. Therefore, it is of great interest to make repair welds on aluminum alloy by MIG welding with pulse current frequency, and to study their mechanical properties and microstructures in the context of pulse frequency.

This work explores how pulsed MIG welding process can contribute for repair welding for aluminum alloy rolling stocks and how the pulse current frequency affects mechanical properties. This work focuses on the properties of aluminum welding repairs welded at different frequencies using pulsed MIG welding process by examination of the macrostructure, microstructure, and distributions of porosity in weld metal and hardness, tensile and bending tests.

2. Materials and Methods

The base material for investigation was a commercial 6082-T6 aluminum alloy with the thickness of 4 mm. The filler wire used in this work was 5356 with a diameter of 1.2 mm. The chemical compositions of aluminum alloy 6082-T6 and filler 5356 are stated in Table 1. Plates of 150x300x4 mm were prepared for butt joints as shown in Figure 1. After that, the pulsed MIG welding process was performed using Fronius TransPuls Synegic 4000 Inverter type with two types of pulse current frequencies, 1.5 Hz and 5 Hz at a constant mean current of 135 A under a controlled atmosphere of relative humidity lower than 60 percent. The welding parameters for both new and repair welding are shown in Table 2. Firstly, new welds were produced and left to cool down to ambient temperature. Then, the repair welding was made by welding again after removing the bead of the new weld by grinding. The welding sequence is also depicted in Figure 2. All the welding conditions are kept constant during welding and at least 8 samples were prepared for each condition to distinguish their mechanical properties and microstructures in the context of pulse frequency.

All welded samples were then analyzed by macrostructure, microstructure, and density of porosity, hardness, tensile and bending properties after cutting the samples. The transverse section of the weld joint was polished and then etched with HF reagent according to standard metallographic procedure. Macro- and microstructures were studied using optical microscope (Olympus SZ2-ET and Olympus Scope.A1) and SEM (FEI, Quanta 400). The image analysis of the porosity of the weld metal in respect of the proportional area of pores and weld metal was carried out using Image J software. Micro Vickers hardness was tested using Zwick/Roell ZHU hardness tester at every 1mm interval under a constant load of 100 gf along the transverse section of welding parts through weld metal, heat affected zone and base metal. In addition, destructive tests were performed to evaluate tensile and bend properties, whose samples were prepared in accordance with AWS D1.2 (Hinostroza, n.d.) shown in Figure 3. Two samples for tensile test and four samples for bend test were prepared in this experiment according to AWS D1.2. Hounsfield model H100KS universal machine was used for tensile test and bending machine was made by Department of Mining and Materials Engineering, Faculty of Engineering, PSU, in accordance with AWS D1.2.

Table 1. Chemical compositions of 6082-T6 aluminum alloy and filler wire

Type	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 6082-T6	0.9	0.2	-	0.4	0.9	-	-	-	Bal
Filler 5356	0.05	0.10	0.006	0.13	4.88	0.12	0.006	0.09	Bal

Table 2. Pulsed MIG welding parameters

Type	Mean current (A)	Peak current (A)	Background current (A)	Volt (V)	Gas flow (l/mm)	Speed (cm/min)	Humidity (%)
Frequency 1.5 Hz	135	148	114	19-21	20-25	45-60	45-60%
Frequency 5 Hz	135	151	122	19-21	20-25	45-60	45-60%

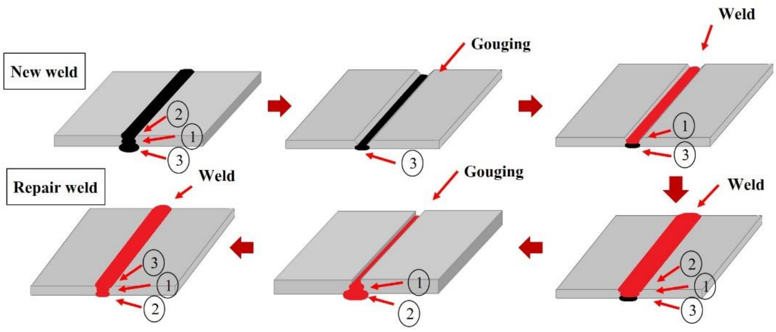

Figure 1. Joint Characteristics and welding sequences for new weld and repair welding

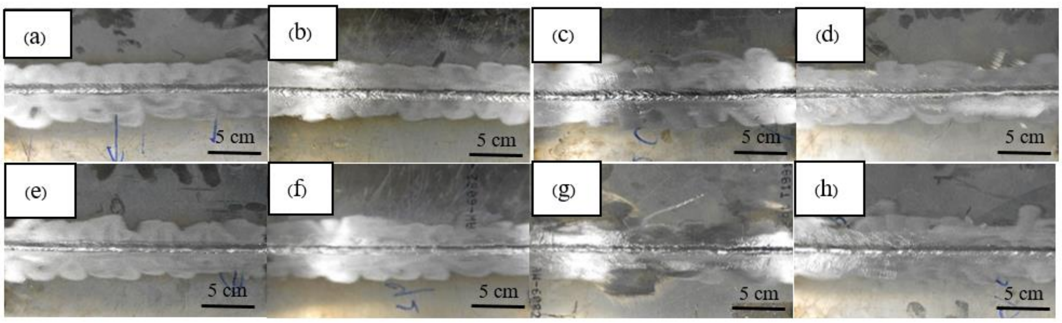

Figure 3. Physical characteristics of welding parts operated at alternative frequencies; new weld (a) front and (b) back (1.5 Hz), repair weld (c) front and (d) back (1.5 Hz), new weld (e) front and (f) back (5 Hz), repair weld (g) front and (h) back (5 Hz)

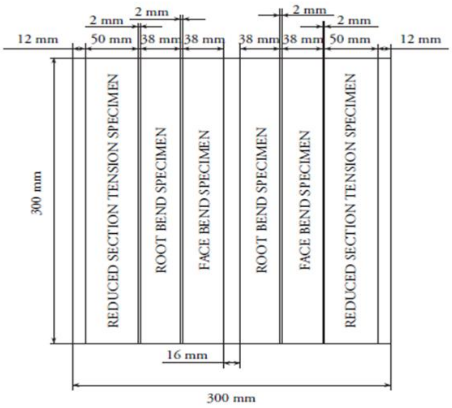

Figure 2. Specimens from welded plates (Hinostroza, n.d.)

3. Results and Discussion

3.1 Physical characteristics and porosity

Figure 3 shows physical characteristics and bead appearance of new and repair welds obtained from the mean current of 135A with 5356 filler at different frequencies of 1.5 and 5 Hz. It could be observed that both welded samples revealed sound weld beads on both front and back sides of the seam. No visual defects such as undercut, overlap, or cracks were observed in all the welded samples.

The cross-sectional macrographs of the repair welding samples under different frequencies are shown in Figure 4. The macrographs indicated good penetration of the weld joints in both samples. However, it was found that porosity distributed around the weld metal. On the other hand, porosities in the weld metal with the applied pulse current frequency of 1.5 Hz were bigger in size.

The formation of the gas porosity, also called hydrogen porosity in the weld is mainly related to the large difference of hydrogen solubility in liquid and solid states during the transformation of liquid to solid states in the solidification process (Mathers, 2002). Porosity area (%) measurement was carried out by using image J analyzing software. Figure 4 depicts the distribution of pores in the weld metal of welding repairs at frequencies of 1.5 Hz and 5 Hz, respectively. Porosity areas (%) in the weld metals with different conditions are summarized in Figure 4 (e). It can be seen from the figures that the porosity area (%) generated in different weld metals varied in the range of 3.1-6.8%. Among them, the repair welds showed higher porosity area (%) than the new welds. This can be attributed to the fact that the repeating of welding pass has more tendency to be contaminated/introduced by hydrogen came from hydro carbons and moisture from the welding materials and environment, and consequently leads to produce higher porosity in weld metal (Wang *et al.*, 2018).

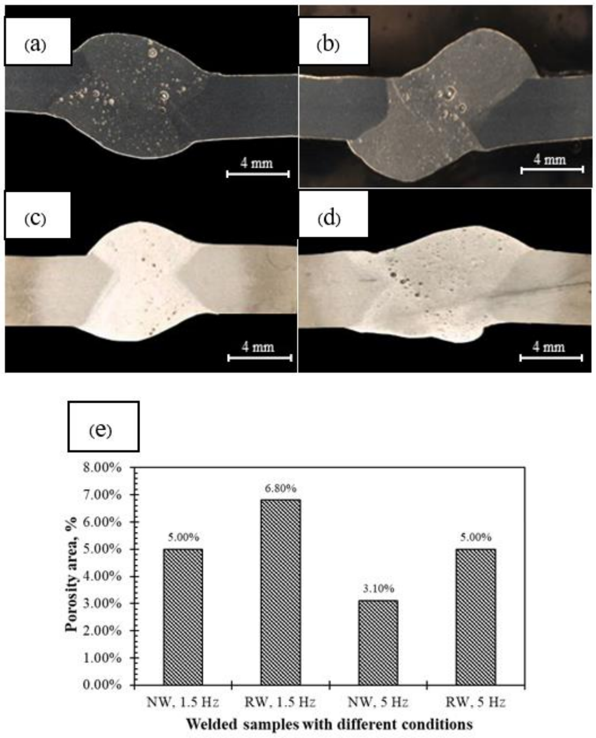

Figure 4. Micrographs of weld joints operated at different frequencies, (a) NW 1.5 Hz, (b) RW 1.5 Hz, (c) NW 5 Hz, (d) RW 5 Hz, and (e) Porosity (%) of new welds (NWs) and repair welds (RWs) with alternative frequencies

Moreover, in both new weld and repair weld, the porosity area (%) in the weld metals with the applied frequency of 5 Hz was lower with smaller pore sizes than that of the weld metals applied at 1.5 Hz (3.1 and 5% compared with 5 and 6.8%). Results clearly showed that a higher frequency of pulse current waveform benefited for reducing the number of porosities in the weld metal. This could be explained by the fact that weld pool vibrates in step with high pulsation current and as a result, the gas bubbles are shaken out of the weld pool. In other words, the arc force generated by the pulse current frequency causes the stirring of liquid weld pool and thereby it favors the gas bubbles to be escaped easier from the weld pool at a higher pulse frequency (Yang, Qi, Cong, Liu, & Yang, 2013). It is clear that increasing frequency has a beneficial effect on reducing the amount of porosity as well as the size of pores.

3.2. Microstructures

The microstructure of base metal is shown in Figure 5(a) in which the distribution of second phase particles is distinctly observed in Al 6082-T6 solid solution matrix. To distinguish the composition of these particles, SEM equipped with EDS characterization was performed as shown in Figure 5(b) and Table 3. The results reveal that the distributed second phase particles can be seen as white particles (Figure 5(b)) and are rich in Al, Mg, Fe and Al (Table 3), revealing the intermetallic compound type of Al(Fe,Mn)Si (Kumar *et al.*, 2009; Menzemer, Lam, Srivatsan, & Wittel, 1999).

Microstructures of heat-affected zone (HAZ) and weld metal (WM) of welded samples before and after repair welding with different frequencies of 1.5 Hz and 5 Hz are presented in Figure 6. As can be seen in the figure, the different grain structures are distinctly observed in weld samples in which the equiaxed grains appeared at the center of the weld zone and the columnar grains at the edge of the weld zone. It is the evidence of directional solidification with epitaxial growth of weld metal from the edge to the weld center according to the opposite direction of heat flow. In terms of directional solidification, the welds have begun to solidify rapidly at the edges of weld in the form of columnar structures and ended at the weld center in the form of equiaxed structures (Davies & Garland, 1975).

There are two sub-zones in the HAZ depending on the temperature gradient generated during welding: dissolution zone which is close to the weld metal and over-ageing zone which is close to the base metal. As shown in Figure 6(a),(b) and (e), (f), compared with the grain sizes in weld metal, the deformed grains are produced in the HAZ closed to the weld metal (dissolution zone) due to the high temperature enough for recrystallization (450-550 °C) (Fadaeifard, Matori, Garavi, Al-Falahi, & Sarrigani, 2016). Unlikely, due to the outward flow of the temperature from the weld metal, the HAZ far away from the weld metal is affected lower temperatures below 240 °C, decreasing the concentration of precipitates at this zone due to the over-ageing effect compared with that of the base metal (Baskutis, Baskutiene, Bendikiene, & Ciuplys, 2019).

Moreover, the finer grain structures in weld metal welded at a frequency of 5 Hz are smaller than that of the weld metal welded at 1.5 Hz. Apparently, this could be directly attributed to the effect of applied pulse current frequency. The grain refinement occurred at a higher pulse current frequency with the faster cooling rates while other welding parameters are constant (Li, Ma, Gao, & Zhai, 2008).

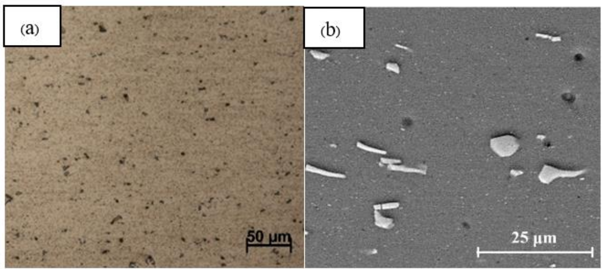

Figure 5. Microstructure of base metal (BM) by (a) optical microscope (b) SEM

Table 3. EDS analysis of 6082-T6 aluminum alloy

Point	Element (weight %)						
	Si	Mg	Fe	Mn	C	O	Al
P1	5.2	-	10.9	6.9	17.9	1.6	57.5
P2	0.5	0.7	-	-	17.9	1.4	79.6

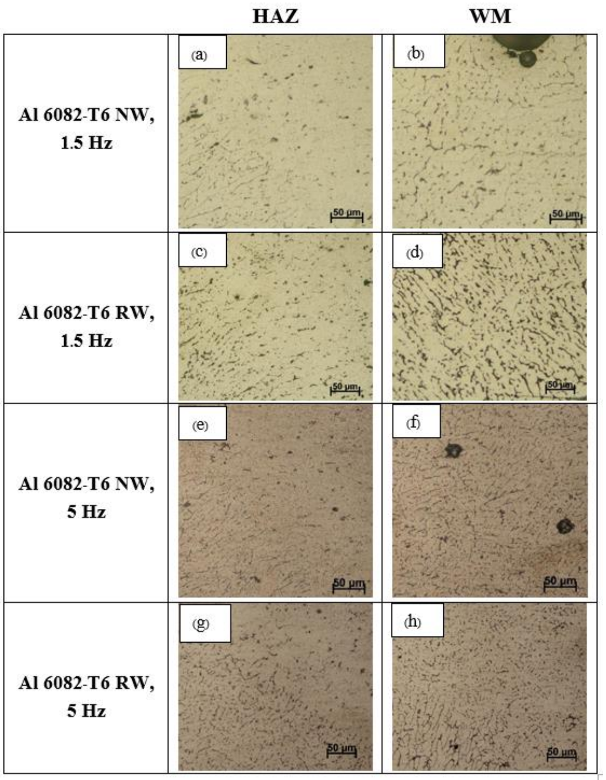

Figure 6. Microstructures of HAZ and WM of Al 6082-T6 new welds (NWs) and repair welds (RWs) operated at different frequencies of 1.5 Hz and 5 Hz.

3.3 Tensile test

Tensile properties of the welded samples with or without repair welding with applied pulse frequencies of 1.5 Hz and 5 Hz are shown in Figure 7. It was found that the tensile and yield strength are decreased after repair welding although the finer grain structures are formed in the repair welds compared with the new welds. Therefore, the loss of strength in repair welds was attributed to the effect of repeated heat cycles and porosity. On one hand, the higher amount of porosity in the weld metal is introduced during the repeated weld seams irrespective of the pulse current frequency as previously discussed in Section 3.1. On the other hand, the repeated heat cycles can induce the over-ageing effect due to higher heat input. Therefore, the repair welds possess lower strength than new welds.

In addition, the weld strengths of the samples made with the applied pulse current frequency of 5 Hz are higher than those made at 1.5 Hz. Increasing the frequency has a beneficial effect on reducing the heat input and the amount of porosity as well as size of pores. The amount of absorbed hydrogen in weld pool during high-frequency welding decreases and the cooling rate is faster in terms of the stirring effect of arc force and vibration effect of weld pool (Gill & Reddy, 2018; Yang *et al.*, 2013). As a result, the welds made with the higher pulse current frequency possess higher strength. Moreover, it can be inferred that all of the welded samples fractured at the weld metals under tensile test because of the presence of porosity. The %-elongation is consistent with their strengths as shown in Figure 7.

3.4 Bending test

Figure 8 shows the bending samples of Al 6082-T6 new welds and repair welds operated at pulse current frequency of 1.5 and 5 Hz. The bending properties of the test samples are summarized in Table 4. The results show that all the test samples possessed satisfied bending properties. Herein, one of the face bend specimens of the repair weld made with pulse current frequency of 1.5 Hz ruptured at weld metal. This can be attributed to the presence of the high fraction of porosity in the weld metal. Therefore, it can be deduced that the repair welds made with higher pulse frequency can provide superior bending property.

3.5 Hardness test

Vickers hardness of weld joints was measured at distance of 1 mm on either side of the weld center line. Hardness profiles across the base metal, heat affected zone, weld metal of new welds and repair welds operated at different frequencies of 1.5 and 5 Hz are shown in Figure 9. The similar hardness profiles are observed in all welding samples wherein the repair welds show the slightly lower hardness values than the new welds because the repeating the heat input in repair weld samples reduces the hardness. The variation of hardness values of all samples directly reflects its formation of microstructures. In all cases, the highest hardness is observed at the base metal. The hardness is obviously increased from the weld metal to HAZ where grains recrystallization occurred, because of the formation of the finer irregular grains in this zone (Moreira *et al.*, 2009). Herein, the lowest hardness is observed in the over-ageing zone of heat affected area. The loss of hardness in this zone resulted from the decreasing of the amount of precipitates in the matrix on approaching from the base metal to the fusion boundary (Missori & Pezzuti, 1997). Nonetheless, the

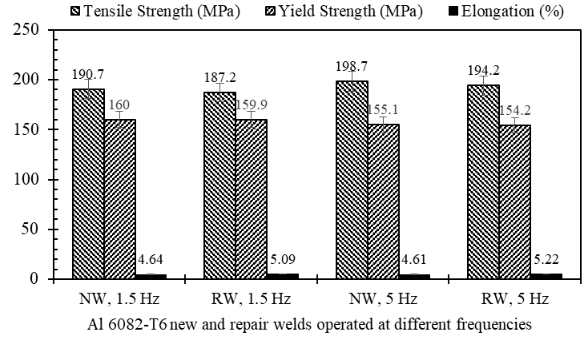

Figure 7. Effect of pulse current frequency on tensile strength

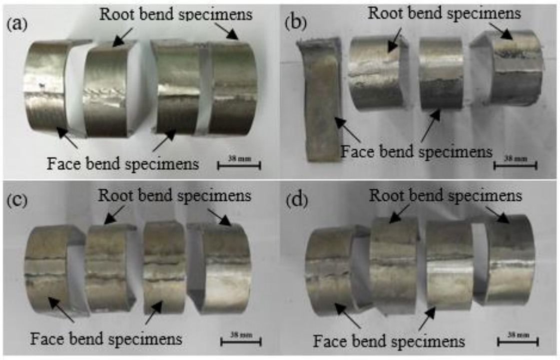

Figure 8. Bending samples of Al 6082-T6 new welds and repair welds with pulse frequencies of 1.5 and 5 Hz; (a) NW, 1.5 Hz, (b) RW, 1.5 Hz, (c) NW, 5 Hz, (d) RW, 5 Hz

Table 4. Bending results of the welded samples with pulse current frequencies of 1.5 and 5 Hz

Welded samples	No. of test specimen	No. of passed specimen
Al 6082-T6 NW, 1.5 Hz	4	4
Al 6082-T6 RW, 1.5 Hz	4	3
Al 6082-T6 NW, 5 Hz	4	4
Al 6082-T6 RW, 5 Hz	4	4

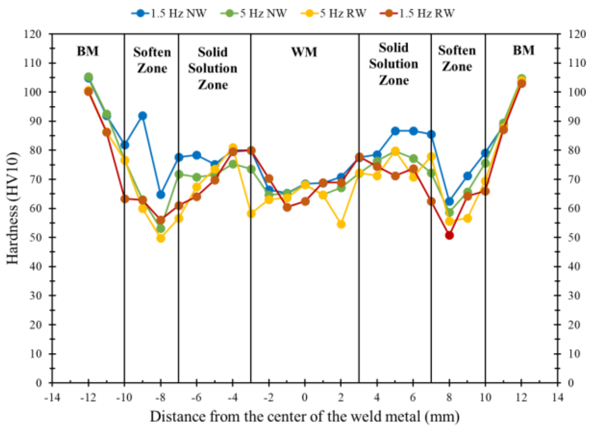

Figure 9. Hardness profiles of welded samples operated at different frequencies of 1.5 Hz and 5 Hz.

experimental results showed that the mechanical property of the aluminum repair welding using pulse current frequency was not quite different from that of new welds and provided the satisfying mechanical property.

4. Conclusions

The analysis of the mechanical properties of repair welds using pulse current can be summarized as follows:

1. The formation of grain size and structures depend on the applied pulse current frequency. The finer grains are produced at a higher pulse current frequency with the faster the cooling rates.
2. Increasing the frequency has a beneficial effect on reducing the amount of porosity as well as the size of pores. The amount of absorbed hydrogen in weld pool during welding at high pulse frequency decreases in terms of the stirring effect of arc force and vibration effect of weld pool.
3. The variation of hardness values in weld samples directly reflects its formation of microstructures. The lowest hardness is observed in the over-ageing zone of heat affected area. The loss of hardness in this zone resulted from the decreasing of the amount of precipitates on approaching from the base metal to the fusion boundary.
4. The repair welds showed slightly lower hardness values than the new welds because of the repeating heat input. In addition, the bending property of repair weld using high pulse frequency exhibited greater bending resistance.
5. The tensile strength decreased after repair welding irrespective of pulse current frequency because of the greater heat input and high fraction of porosity. Moreover, the repair weld welded using high pulse current frequency provided the higher tensile strength, suggesting that the high pulsed MIG welding is preferable for the repair welding of 6082-T6 aluminum alloy.

In addition, this study clearly showed that the pulsed MIG welding process has beneficial effect on the metallurgical and mechanical properties of repair welding of 6082-T6 aluminum alloy. The experimental results suggested that the pulsed MIG welding process with pulse current frequency of 5 Hz at a constant mean current of 135 A under a controlled atmosphere can provide quality repair welds of 6082-T6 aluminum alloy (4 mm thickness) welded with ER 5356 filler wire.

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