Influence of New Welding Technology and Wire Type on Welding Reliability of Aluminum Alloy 6061-6101

Jintao Su¹,*, Ling Zheng¹, * and Bangdong Wang², b
¹State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing, China
²Saic-iveco Hongyan Commercial Vehicle Co., Ltd, Chongqing, China
*Corresponding author e-mail: zling@163.com, *nvh2012@163.com, bbangdong@163.com

Abstract. Aluminum alloy materials have low melting point and high plasticity, therefore, in the field of material welding has been widely used. In order to study the influence of new welding process parameters on the welding reliability of aluminum alloy materials (6061-6101), this paper studied the welding properties of four kinds of welding wires under the condition of new welding process parameters (100A welding current, welding speed of 5mm/s). The results showed that compared with the traditional welding process, the new welding process increased the speed by 2.5 times and reduced the welding current by 1 times. The welding reliability meets the design requirement. The welding wires (ER5356, ER4043) have no obvious bubble in the weld area. The maximum tensile strength of the four types of wire is 141.14MPa, which is 1.6 times of the yield limit. The new welding parameters have good tensile resistance for aluminum alloy materials. No obvious corrosion defects were found in the corrosion test.

1. Introduction
The material aluminum has the characteristics of low density, low melting point and high plasticity. This material can be easily processed into various plates. However, aluminum has low tensile strength and is not suitable for welding. Through continuous in-depth research and production practice [1-5], adding alloy elements or heat treatment technologies to improve the strength performance of aluminum, more and more attention has been paid to the material industry. As a non-ferrous metal material, aluminum alloy has been applied in the industrial manufacturing fields such as aerospace [6-8], automobile [9], ship [10-14], high-speed train etc [15-16]. With the continuous development of industrial economy, the welding demand of aluminum alloy is gradually increasing [17], which makes the welding research of aluminum alloy more and more valued by scholars. Fratini, Buffa et al. [18] adopted friction stir welding for 3mm thick AA2024 and 6082-T6 aluminum alloy joints, and established a numerical model, which simulated and compared the internal plastic metal flow in the welding of the two aluminum alloy joints. The results show that it is easier for 6082-T6 aluminum alloy with low strength and high hardness to obtain high joint performance when the joint is friction stir welding with AA2024 aluminum alloy with high strength and low hardness. Penalva et al. [19] studied the defects in the friction stir welding of aluminum alloy joints. All the welding process parameters selected in the experiment showed different...
degrees of welding defects. When the welding speed increased from 7mm/s to 10mm/s, the defect area increased. Xia [20] studied the welding reliability of MB8 magnesium and aluminum alloy at the welding current of 140-160A and the welding speed of 2.5mm/s. At the same time, the fracture fatigue limits of magnesium aluminum alloy and welded joint were analyzed. Diao [21] conducted joint welding tests on Al-Zn-Mg aluminum alloy plate in the condition of welding current 200-215A and welding speed of 10mm/s, and the results showed that most areas of welding structure of ER5356 wire were small equiaxial crystals, and the welding reliability was high. Liu et al. [22] studied the microstructure and properties of AA7075-T651 aluminum alloy plate double-pulse MIG welding seam with ER5556 and ER5356 welding wire, and concluded that the welding seam properties filled with ER5556 welding wire were better. At present, for the research on the welding reliability of welding wire in the literature, the welding current under control is > 140A and the maximum current is 215A. Welding speed control in 2.5 mm/s at low speed or high speed 10 mm/s. However, for welding current of 100A, the speed of 5 mm/s influence on the reliability of the welding test condition has not reported, on the other hand, in the current literature to the selection of different welding wire are mainly based on ER5556 and ER5356 wire, such as for aluminum alloy similar to that of the parent metal welding wire 6101, 6061, and the differences of traditional welding ER5365 reliability, previous literature has not reported. Therefore, this paper verifies the low voltage current 100 A, welding speed under the condition of medium speed of 5 mm/s, different welding wires ER5356, ER4043, aluminum alloy welding wire 6101, 6061 welding reliability. For different types of welding wire, the difference between the new welding process parameter and the high current welding process parameter is verified by conducting the following tests, including welding tests, tensile strength tests and corrosion tests.

2. Experimental details

In this paper, 6061 aluminum alloy is selected as the material to produce strengthened beams and fixed plates, and 6101 aluminum alloy is selected as the material to produce energy absorber box. In order to obtain better welding performance in connecting parts, the welding process of 6061 aluminum alloy and 6101 aluminum alloy was studied. This paper studies the welding reliability of different welding wires under the condition of low current 100A and welding speed of 5mm/s. The aluminum alloy sheets (6061 and 6101) are respectively welded with ER4043 welding wire, ER5356 welding wire, 40x2mm 6061 aluminum welding wire, 40x2mm 6101 aluminum welding wire. The chemical compositions of aluminum alloy 6061 and 6101 and ER4043 and ER5356 welding wires are shown in Table 1 and 2, and the welding process parameters are shown in Table 3. At the same time, the acid spray test is carried out on the welded joint. Corrosion condition: the sampling time is set as 12, 24, 72, 96 and 168 hours.

The sample making and testing process is as follows:

1. As shown in Fig. 1, the welded plates (42mm x 160mm x 3mm) were processed into samples. Then the tensile test is carried out. The microstructure of the weld was observed under the microscope.
2. The mechanical properties of the weld were obtained by strength test.
3. The microstructure of different wire structures (weld zone, thermal response zone, and fracture zone) was examined and observed.
4. Acid spray test was carried out according to the above experimental conditions.

Table 1. Chemical compositions of 6061 and 6101 aluminum alloys.

| Materials | Si  | Mg  | Fe  | Cu  | Cr  | Mn  | Zn  | B  | Ti  |
|-----------|-----|-----|-----|-----|-----|-----|-----|----|-----|
| 6061      | 0.40-0.80 | 0.80-1.20 | 0.0-0.70 | 0.15-0.40 | 0.04-0.35 | 0.15 | 0.25 | 0.15 |
| 6101      | 0.30-0.70 | 0.35-0.80 | 0.50 | 0.10 | 0.03 | 0.03 | 0.10 | 0.06 |

Table 2. Chemical composition of 5356 and 4043 welding wire.

| Welding wire | Zn  | Mg  | Cu  | Cr  | Mn  | Ti  |
|--------------|-----|-----|-----|-----|-----|-----|
| ER5356       | 0.10 | 4.5-5.5 | 0.10 | 0.05 | 0.20 | 0.06-0.20 |
| ER4043       | <0.1 | <0.20 | <0.3 | / | <0.05 | <0.15 |
### Table 3. Welding technology parameters.

| Welding current | voltage | Gas flow | Welding speed |
|-----------------|---------|----------|---------------|
| I/A             | U/V     | Q/(L·min⁻¹) | v/(mm·s⁻¹) |
| 100             | 23.5    | 20-22    | 5             |

#### Figure 1. Tensile specimen map.

#### 3. Results and discussion

3.1. *Quality analysis of welding joint*

Fig. 2 shows the macroscopic diagram of welding joints of different welding wires. From the appearance, it can be seen that the welding seam of 5356 welding wire is long and thin with narrow welding width and good surface profile. There is a small amount of weld bead locally. The other three types of welding wire surfaces are not concave and convex without rules. Therefore, the welding seam is wide and the appearance is not good. In particular, the widths of the 6101 and 6061 welding seams wear not even, with a contraction groove on the edge and a crack in the middle of the welding seam. The overall appearance of 5356 welding wire has the best welding quality and can meet the welding requirements [20-22]. Cracks are the most common defects in welding area. Macroscopic cracks seriously affect the performance and safety reliability of welded structures. Compared with the other two types of welding wire, ER5356 and ER4043 basically have no cracks. In particular, there were no defects or obvious bubbles in the microscopic observation of 5356 welding wires. Double-pulse MIG welding of 5356 welding wire is used to weld 6061-6101 aluminum alloy joints. Because the Mg content of ER5356 welding wire is higher than that of other welding wire types [23], its performance and microstructure are superior. This paper verifies that the welding stability of ER5356 and ER4043 welding wires has no obvious difference under the conditions of high and low current, and is superior to that of aluminum alloy welding wires 6101 and 6061.

#### Figure 2. Weld joint quality of different wire (a) 5356 welding wire (b) 4043 welding wire (c) 6061 welding wire (d) 6101 welding wire.
Figure 3. Metallographic structure of welding joints of different welding wires (100 x): (a) 5356 welding wire (b) 4043 welding wire (c) 6061 welding wire (d) 6101 welding wire.

3.2. Mechanical properties of welded joints
Table 4 shows the tensile test results of welded samples. The results show that the joint tensile strength of ER4043 welding wire, aluminum alloy welding wire 6101, 6061 is poor, the minimum tensile strength of 62.2MPa. The tensile strength of ER5356 welded joint is 141.14MPa. Different welding processes have great influence on the tensile strength of joints, and welding current and welding speed are the main factors. Under the condition of 100A welding current and 5mm/s welding speed, the tensile strength of ER5356 wire joint is lower than 200A welding current and 2mm/s welding speed [21]. In addition, the tensile strength of welded joints is related to the welding bubble and welding width. Although the tensile strength of the new welding process parameters are lower than that of the reference [21], the tensile strength is greater than the yield limit and far greater than the allowable stress of aluminum alloy materials under the working condition. Therefore, the new welding parameters meet the strength requirements. (Notes: the allowable stress of the material is equal to the yield of the material divided by the safety factor, and the safety factor is 1-1.5)

| welding wire | strength of extension/MPa | yield strength/MPa |
|--------------|---------------------------|-------------------|
| 5356/(Welding seam breakage) | 141.14 | 86.55 |
| 4043/(Welding seam breakage) | 107 | 94.3 |
| 6101/(Welding seam breakage) | 105 | 71.97 |
| 6061/(Welding seam breakage) | 62.2 | 54.19 |

3.3. Hardness test results of weld, heat affected zone and base metal
As the human error in the welding process is relatively large, in the tensile test, some welding samples broke outside the welding seam, which failed to reflect the strength of the welding seam. Therefore, hardness testing method is adopted to characterize the soft and hard degree of metal materials, which can reflect the difference of chemical composition and structure of metal materials sensitively. Wechsler hardness (HV0.5) was used in this test. Due to the local and instantaneous action of heat source in the welding process, the chemical composition and structure of the welding joint are not even. Therefore, data fluctuation is normal in the testing process. Fig. 4 shows the hardness curves of different welding wire joints. Within the three zones, the minimum hardness of the thermal response zone is 55HV, mainly because of welded joint in thermal response must be "softening phenomenon", and literature [21,22] the weld hardness distribution trend is consistent, but, due to differences in welding process, when the welding current by 200 a, down to 100 a, thermal response area ER5356 joint hardness HV reduced to 55 from 76 HV, so the welding current for joint hardness has certain positive correlation, as the disappearance of the thermal response area "softening phenomenon", in the weld zone, four kinds of welded joint was increased, the hardness of the test results show that the ER5356 welding wire is well matched with the 6 series aluminum alloy. The strength of the base material, the welding seam and the heat-affected zone are close, and the welding stress is small.
3.4. Metallographic structure of the welded joint

The microstructure of the surface is different from that of the welding core and the base material because of the difference between the plastic flow mode of the metal on the welding surface and the welding core area. In the process of MIG welding, the heat input is increased, and it will stay at high temperature for a long time. Fig. 5 shows the microstructure of welded joints with different welding wires. As can be seen from the figure, the microstructures of wires 5356 and 4043 are obvious due to the effect of thermal cycle, using the two kinds of welding wire welding joint of grain becomes bulky of heat affected zone. Especially when 5356 welding wire is used, the microstructure of weld and heat affected zone is large, and the grain arrangement is not close enough, which is also the reason why the hardness of weld and heat affected zone is low when 5356 welding wire is used. The degree of welding hardness is not only related to the welding wire, but also has a lot to do with the microstructure. The weld and heat affected zone of 6101 and 6061 are not obvious, the grain size is not big, and the arrangement is close, so the hardness of the two kinds of weld is higher. From the point of microstructure, the edge of weld joint is close. On the whole, the width of the heat affected zone is narrow and has little influence on the base metal. When the welding wire ER5356 and ER4043 are welded, the columnar crystals are relatively developed and the dendrites are relatively thick, which is consistent with the literature [22-23]. The welding crystals of aluminum alloy welding wire 6101 and 6061 are small, and there are more eutectic production at low melting point in the grain boundary, with great brittleness and stronger crack tendency, which have a great impact on the tensile properties of weld metal.

3.5. Effect of corrosion on welded sample

Fig. 6 shows the morphology of the welded samples after different corrosion times. It can be seen from the figure that the corrosion products of the aluminum alloy samples with white particles appeared on the welding surface. The corrosion phenomenon belongs to the mild corrosion. When the corrosion time is 12h, the non-corrosion film on the weld surface appears, and there is little difference between the color of the weld and the base material before the corrosion. When the time is 96h, the surface of the weld is covered with gray corrosion film, and both the weld and base material have white granular corrosion products. At 168h, the weld seam and surface became darker, gradually turning gray black and the number of white corrosion particles increased, but there was no foaming phenomenon. The result of the test shows that the welding joint, thermal influence area and base material area of the four types of welding wire are all discoloured, and there is no obvious corrosion. The results of the corrosion test are related to the content of Zr trace elements in the four kinds of welding wires. According to the observation of the surface color of the corrosion sample, ER5653 welding wire has a good corrosion resistance [24].
Figure 5. Metallographic structure of welding joints of different welding wires (100 x): (a) 5356 welding wire; (b) 4043 welding wire; (c) 6061 welding wire; (d) 6101 welding wire.

Figure 6. Corrosion performance results: (a) 5356 welding wire; (b) 4043 welding wire; (c) 6061 welding wire; (d) 6101 welding wire.

4. Conclusion
In this paper, the welding reliability of aluminum alloy 6061 and 6101 base metal is studied. New welding process parameters (welding current 100A, welding speed 5mm/s) are adopted to compare the welding results of four different welding wires. The following conclusions are drawn from the experiment:

1. Under the new welding process parameters, there are few defects in ER5356 welding wire joints and no obvious bubbles in the welding zone. There are a few cracks in ER4043, aluminum alloy welding wire 6101, and 6061 welding joints.

2. Under the new welding process parameters, the tensile test results show that the tensile strength of the welding zone of the four kinds of welding wires, the welding current of 200A and the welding speed of 2mm/s all decrease, but all are greater than the yield limit. The maximum tensile strength of ER5356 welding wire still meets the strength requirements.

3. In the hardness test of the new welding process parameters, the welding hardness of ER5356 welding wire is close to the base metal, the hardness of ER4043, aluminum alloy welding wire 6101, 6061 joint is higher than the base metal, and the lowest hardness appears in the thermal response zone.

4. The corrosion effect of the new process parameters meets the requirements without obvious corrosion defects.
References

[1] Ševčíková, J., Kocich, J. Fatigue Limit Decrease Caused by Atmospheric Corrosion in the Weathering Steel 15 127 Materials Engineering (Materiálové inžinierstvo) 6 1999: pp. 39 – 44 (in Slovak).

[2] Zhen, R., Fang, X.X., Sun, Y.S., Yang, X. Progress in Research on Fatigue Behavior of Wrought Magnesium Alloys Materials Review 24 (9) 2010: pp. 130 – 133. (in Chinese)

[3] Somekawa, H., Maruyama, N., Hiromoto, S., Yamamoto, A., Mukai, T. Fatigue Behaviors and Microstructures in Extruded Mg-Al-Zn Alloy, Materials Transaction 49 (3) 2008: pp. 681 – 684. http://dx.doi.org/10.2320/matertrans.MRP2007292

[4] Morita, S., Tanaka, S., Ohno, N., Kawami, Y., Enjoji, T. Cyclic Deformation and Fatigue Crack Behavior of Extruded AZ31B Magnesium Alloy Materials Science Forum 638 – 642 2010: pp. 3056 – 3061.

[5] Ishisara, S., Nan, Z., Goshima, T. Effect of Microstructure on Fatigue Behavior of AZ31 Magnesium Alloy Materials Science and Engineering A 468 – 470 2007: pp. 214 – 222.

[6] Zhen, R., Fang, X.X., Sun, Y.S., Yang, X. Progress in Research on Fatigue Behavior of Wrought Magnesium Alloys Materials Review 24 (9) 2010: pp. 130 – 133. (in Chinese)

[7] Yu, Q., Zhang, J.X., Jiang, Y.Y., Li, Q.Z. An Experimental Study on Cyclic Deformation and Fatigue of Extruded ZK60 Magnesium Alloy International Journal of Fatigue 36 (1) 2012: pp. 47 – 58.

[8] Williams J C, Starke Jr E A. Progress in structural materials for aerospace systems [J]. Acta Materialia, 2003, 51(19): PP. 5775-5799.

[9] Gierenz, G., Karmann, W. Adhesive and Adhesive Tapes, Wiley-VCH Verlag gmbh, 2001: 138 p.

[10] Jones, I.-A., Wise, R.-J. Novel joining methods applicable to textiles and smart garments. Paper presented at Wearable Futures Conference, University of Wales, Newport, Wales, 14-16 September 2005. (accessed 18 July 2014).

[11] Bhat, G.-S., Jangala, P.-K., Spruiell, J.-E. Thermal bonding of polypropylene nonwovens: effect of bonding variables on structure and properties of the fabrics Journal of Applied Polymer Science 92 2004: pp. 3593 – 3600.

[12] Hedge, R.-R., Bhat, G.-S., Campbell, R.-A. Thermal bonding of polypropylene films and fibers Journal of Applied Polymer Science 110 2008: pp. 3047 – 3058.

[13] Crupi, V., Marinò, A., Biot, M., et al. Fatigue Prediction by Thermographic Method of Aluminum Alloy 6082 Panels: Comparison Between FSW and MIG Welding. Journal of Ship Production 23 (4) 2007: pp. 215-222.

[14] Miller W S, Zhuang L, Bottema J, et al. Recent development in aluminium alloys for the automotive industry. Materials Science and Engineering: A, 2000, 280 (1): 37-49.

[15] Song, M. K., Noh, H. C., Choi, C. K. A new three-dimensional finite element analysis model of high-speed train–bridge interactions. Engineering Structures 25 (13) 2003: pp. 1611-1626.

[16] Fedorova, M., Sivaselvan, M. V. An algorithm for dynamic vehicle-track-structure interaction analysis for high-speed trains. Engineering Structures 1482017: pp. 857-877.

[17] Seeger, T., Degenkolbe, J., Olivier, R. Admissible Stresses for the Fatigue Design of Weathering Structural Steels after Six Years’ Exposure Stahl Eisen 11 (11) 1991: pp. 101–110 (in German).

[18] Albrecht, P., Lenwari, A. Fatigue Strength of Weathered A588 Steel Seams Journal of Bridge Engineering 14 (6)2009:pp.436-443.

[19] Kocich, J., Ševčíková, J., Bartoš, J. Changes of Fatigue Strength of Atmofix Steel in Process of Atmospheric Corrosion In: Proc. of the Conference Únava materiálů a konstrukcí ÚZVÚ Škoda, Plzeň 1984: pp. 64 – 71 (in Slovak).

[20] Yingxia, Y., Blin H., Mihua J., Zongmin L., Hua M. Fatigue Properties of Welded Butt Joint and Base Metal of MB8 Magnesium Alloy, Materials Science (Medžiagotyra) 22 (3) 2016: pp. 343-347.

[21] Diao, G.Y., Wang, D.L., Li, H.C., Liang, Z.M. Effects of different welding wires on...
microstructure and mechanical properties of pulsed MIG welding of Al-Zn-Mg aluminum alloy
Hot Working Technology 4 (47) 2018: pp. 195-197. (in Chinese)

[22] Liu, C.J., Sun, J., Zhang, W. Different welding wires on 7075 aluminum alloy double pulse MIG effect of welding seam texture and properties
Hot Working Technology 45 (19) 2016: pp. 203-205. (in Chinese)

[23] Yi, J., Li, L.X., Liu, K.Y. Influence of wire composition on microstructure and properties of 6061-T6 aluminum alloy double pulse MIG welding seam
Weapon Material Science and Engineering 38 (3) 2015: pp. 26-30. (in Chinese)

[24] Dang, J.Z., Huang, Y.F., Cheng, J. Effect of Sc and Zr on microstructures and mechanical properties of as-cast Al-Mg-Si-Mn alloys
Transactions of Nonferrous Metals Society of China 19 (3) 2009: pp. 540-544.