Effect of Post-weld Heat Treatment on Microstructure and Mechanical Properties of Al-Zn-Mg-Cu Alloy Welded Joint

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Abstract. Metal inert-gas welding (MIG) test was carried out using ER5183 welding wire as filler metal and Al-4.8Zn-1.6Mg-0.16Cu alloy profile as base material. Different post-weld heat treatment processes were adopted for Al-4.8Zn-1.6Mg-0.16Cu alloy welded joints. The effects of different post-weld heat treatment processes on the microstructures and mechanical properties of welded joints were studied by means of hardness test, microstructure observation and scanning electron microscopy analysis. The results show that the mechanical properties of welded joints can be improved by artificial aging treatment after welding. At the same time, the comprehensive mechanical properties of re-solution and aging after welding will be significantly improved. The inhomogeneity of welded joints and the distribution of strengthening phases will also be improved, the softening of heat affected zone will almost disappear, and the strength of welded joints will be restored.

1. Introduction

With the rapid development of rail transit industry, energy saving, emission reduction and high-speed safety have become the focus and development direction of major rail transit enterprises and the best solution to this problem is applications of lightweight car body materials [1-3]. Medium and high strength Al-Zn-Mg-Cu alloys have excellent mechanical and technological properties after solution and aging (usually in T6 state) [4-7], so they are ideal materials for lightweight body. Aluminum alloy body manufacturing is mostly based on MIG or TIG arc welding with large heat input [8-11]. The joint softening after welding is serious, which directly affects vehicle safety and service life. Due to the influence of welding heat input, the weld is prone to second phase segregation, intergranular corrosion and stress corrosion [12]. Usually, the welding performance can be improved by post-weld heat treatment [13, 14].

Therefore, the effect of different post-weld heat treatment processes on the microstructures and mechanical properties of MIG welded joints is studied in this paper. These studies will provide theoretical basis for expanding the engineering application of Al-Zn-Mg-Cu alloys, and have important significance for promoting the development, design and in-depth study of post-weld heat treatment technology of Al-Zn-Mg-Cu alloys.
### 2. Experimental materials and methods

The experimental material is Al-4.8Zn-1.6Mg-0.16Cu alloy. The raw material is melted in smelting furnace and semi-continuous casting machine is used for semi-continuous casting. The Al-Zn-Mg-Cu alloy profile (75×45×5mm) is extruded by 2000 t extruder. T6-treated alloy is obtained by on-line water-cooled quenching. The 100mm profile parallel to the extrusion direction was intercepted as the welding base material, and the filler wire is ER5183 with a 1.2 mm diameter. The chemical composition of base metal and welding wire was determined by ARL 3460 spark direct reading spectrometer. The result of the base metal is: Zn 4.8%, Mg 1.6%, Cu 0.16%, Si 0.09%, Fe 0.15%, Mn 0.41%, Cr 0.12%, and the residual amount is Al. The result of the filler wire is: Zn 0.11%, Mg 4.88%, Cu 0.03%, Si 0.05%, Fe 0.13%, Mn 0.52%, Cr 0.11%, and the residual amount is Al.

The weld joint type and groove size (t1=t2=5mm, ψ=70°, b=0~0.5mm) are shown in Fig. 1. Before welding, pneumatic steel wire brush was used to polish the welded parts on the base metal surface to expose the metallic luster. MIG welding was carried out on the base metal by using the Fornis TPS 5000 welding machine. The welding parameters are as follows: the shielding gas is high purity argon (purity > 99.99%); welding current is 125A; welding speed is 60cm/min; argon flow rate is 20L/min.

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![Figure 1. Weld joint type and groove size](image1)

The penetration test of the welded samples is carried out according to NB/T 47013.5-2015 "Non-destructive Testing of Pressure Equipment Part 5: Permeation Testing". The results meet the requirements. The welding samples and penetration test results are shown in Figure 2. The samples are heat treated after welding. The post-weld heat treatment process is shown in Table 1.

![Figure 2. Weld joint after penetration detection](image2)

Tensile tests were carried out with SHIMADZU 100 kN electronic universal testing machine at a loading rate of 10mm/min. Samples were prepared according to the standard requirements of GB/T 2651-2008 tensile test method for welded joints. Three samples were tested in each group, and the average value was taken as the test result. The sampling position of tensile samples was shown in Figure 3. Tensile properties of wide and narrow surfaces of rectangular tubes were measured separately. FEI Inspect S50 type scanning electron microscope (SEM) was used to observe the tensile fracture morphology. Microstructure was observed by means of Leica DMI 5000M metallographic microscope.
The KB30S type Vickers hardness tester is used to test the hardness. The testing position is one-half of the wall thickness in the horizontal direction. The testing load is 0.5kg, and the distance between testing points is 0.5mm. The hardness testing position is shown in Figure 4.

**Table 1. Post-weld heat treatment process**

| Welding condition | post-weld heat treatment process | parameters          |
|-------------------|---------------------------------|---------------------|
| S1                | without heat treatment          | -                   |
| S2                | Aging treatment                 | 150°C for 6 h       |
| S3                | solid solution + ageing treatment | 520°C for 30 min+150°C for 8 h |

**Figure 3. Schematic diagram of welding and sampling location (mm)**

**Figure 4. Location of hardness test points**

3. Results and Discussions

3.1. Microstructure

The microstructure of weld zone is typical as-cast microstructure of aluminum alloy, and there is no obvious difference before and after heat treatment. Fig. 4 shows the microstructure of HAZ in different post-weld heat treatment regimes. It can be seen that the heat affected zones of S1 and S2 samples are recrystallized under the influence of welding thermal cycle, and the grains grow up, and there are growing black Mg₂Si phases. After re-solution and aging, the coarse Mg₂Si phase in the heat-affected zone dissolves back, and the dispersed strengthening phase is precipitated again, and the homogeneity of microstructure is improved.

3.2. Hardness

The hardness of different post-weld heat treatment specimens was tested, and the test results are shown in Fig. 6. As can be seen from figure 6, it can be seen that the base metal is less affected by welding heat cycle, and the hardness change trend of S1 and S2 welding specimens is similar, that is, with the increase of distance from the weld, the hardness first increases, then decreases, then increases to the base metal hardness level and remains stable. The lowest hardness of S1 sample is at the weld, the hardness value is 64.0HV, the lowest hardness of S2 sample is 1 mm away from the center of the weld, and the hardness value is 69HV. With the increase of the distance from the weld, the influence of welding heat cycle on the material decreases, and the hardness of HAZ begins to recover to the hardness of base metal. Compared with the untreated sample (S1), the hardness of the weld and HAZ of the S2 sample after post-weld heat treatment has been improved to a certain extent, and the width of HAZ has been narrowed obviously. After re-solution aging treatment, the change trend of hardness of S3 welded joint is obviously different. In addition to the increase of weld hardness, the softening of heat affected zone is significantly improved, and the hardness is obviously restored. The lowest hardness value is 82HV.
Figure 5. Microstructures of HAZ after different post-weld heat treatment: (a) S1, (b) S2, (c) S3

Figure 6. Hardness of welding joints after different post-weld heat treatment

3.3. Tensile test
Table 2 shows the test results of mechanical properties of different post-weld heat treatment samples. Fig. 6 shows the trend of the mean values of the wide, narrow and overall tensile strength of different post-weld heat treatment samples. As shown in Table 2, the overall average tensile strength of base metal is 405 MPa, and the wide side is close to the narrow side. The overall average tensile strength of welded joints without post-weld heat treatment is 263 MPa, and the welding coefficient (joint tensile strength/base material tensile strength) is 64.9%. Tensile strength increased to 285 MPa and the strength coefficient was 70.4% after ageing at 175 C for 6 h. After re-solution and re-aging after welding, the tensile strength reaches 307 MPa and the welding coefficient reaches 75.8%. Compared with the direct aging treatment after welding, the tensile strength and yield strength of the joint after re-solution and re-aging treatment have been improved. The trend of yield strength in Table 2 was further observed, and it was found that the trend coincided with that of tensile strength. However, it can also be seen from Fig. 6 that the strength difference between wide and narrow faces of S3 specimen increases with the increase of tensile strength. This is mainly due to the shorter welds on narrow surfaces, its welding defects are...
always higher than the wide surface, resulting in the overall effect of subsequent heat treatment is still not as good as the wide surface.

| Welding condition | Position | UTS /MPa | E(UTS) /MPa | E(UTS) /MPa | YS /MPa | E(YS) /MPa | E(YS) /MPa |
|-------------------|---------|----------|-------------|-------------|---------|-------------|-------------|
| WM                | Wide plane | 401      | 402         | 405         | 339     | 343         | 341         |
|                   | 400      | 400      |             | 405         | 334     | 339         | 338         |
|                   | Narrow plane | 400     | 407         |             | 340     | 339         | 340         |
| S1                | Wide plane | 288      | 256         | 263         | 190     | 189         | 189         |
|                   | 226      | 226      |             | 263         | 190     | 189         | 189         |
|                   | 253      | 253      |             | 263         | 190     | 189         | 189         |
|                   | Narrow plane | 317     | 269         |             | 188     | 192         | 179         |
|                   | 264      | 264      |             | 263         | 190     | 189         | 189         |
|                   | 227      | 227      |             | 263         | 190     | 189         | 189         |
| S2                | Wide plane | 278      | 279         | 285         | 201     | 203         | 201         |
|                   | 292      | 292      |             | 285         | 201     | 203         | 201         |
|                   | 268      | 268      |             | 285         | 201     | 203         | 201         |
|                   | Narrow plane | 310     | 291         |             | 225     | 216         | 213         |
|                   | 256      | 256      |             | 285         | 201     | 203         | 201         |
|                   | 308      | 308      |             | 285         | 201     | 203         | 201         |
| S3                | Wide plane | 279      | 295         | 307         | 197     | 209         | 209         |
|                   | 307      | 307      |             | 307         | 209     | 209         | 209         |
|                   | 298      | 298      |             | 307         | 209     | 209         | 209         |
|                   | Narrow plane | 327     | 319         |             | 239     | 232         | 222         |
|                   | 333      | 333      |             | 307         | 234     | 232         | 222         |
|                   | 296      | 296      |             | 307         | 234     | 232         | 222         |

**Figure 7.** Tensile strength of welding joints after different post-weld heat treatment

3.4. Fracture Analysis
Fracture morphology of tensile specimens after different post-weld heat treatment was observed by SEM, and the results were shown in Fig. 8. The fracture morphology of S1 and S2 specimens is a mixed mode of dimple fracture and cleavage fracture, but the number and size of dimples are quite different. The dimple size of S1 is larger and less than that of S2, and the cleavage surface area is larger. This indicates that there are more second phases in the thick fracture position of S1, which is easy to cause stress concentration cracking and promote crack propagation. S3 sample fracture morphology dimple size is uniform, dimple aggregation to form holes, tear edge is obvious, there are obvious holes, is formed by
welding seam pore or dimple aggregation. The dimples size of S3 sample was uniform, and the dimples aggregated to form holes with obvious tearing edges. And there are obvious holes in the fracture, which are formed by the coalescence of weld pore or dimple. Samples S1 and S2 are subdivided into solution zone and over-aging zone by welding heat cycle. The temperature of heat affected zone near the weld is higher than that of Mg and Si atoms, and the Mg2Si strengthening phase dissolves back, that is to say, the solid solution zone is formed. However, the temperature in the heat affected zone far from the weld is lower than the solution temperature of Mg and Si atoms. The agglomeration and growth of Mg2Si strengthening phases occur, that is, the over-aging zone is formed, and the mechanical properties and plasticity of the joints decrease. However, after the post-weld heat treatment of S2 sample, the inhomogeneity of microstructure and distribution of strengthening phases are improved, so the tensile strength is improved. Relative to the microstructure of heat affected zone of S1 and S2 samples, Mg and Si elements almost completely re-solution after Solution-Aging, the softening zone of heat affected zone almost disappears, and the strength of joints increases greatly.

Figure 8. SEM images of tensile fracture sample: (a) S1, (b) S2, (c) S3

4. Conclusion
(1) The minimum hardness of the weld increased from 64 HV to 69 HV, the tensile strength increased from 263 MPa to 285 MPa, and the yield strength increased from 189 MPa to 209 MPa after post-weld heat heat treatment at 150°C for 6 h.
(2) After post-weld heat treatment at 520°C for 30 min & 150°C for 8 h, the strength and hardness of the joints were greatly improved, the minimum hardness of the weld increased from 64 HV to 84 HV, the tensile strength increased from 263 MPa to 307 MPa, and the yield strength increased from 189 MPa to 220 MPa.
(3) After aging treatment, the inhomogeneity of the microstructure and the distribution of strengthening phases are improved. After re-solution and aging treatment, the Mg2Si phase is dissolved and the dispersed strengthening phases are precipitated again. Therefore, post-weld heat treatment is an effective way to improve the strength of welded joints of heat-treated strengthened aluminium alloy.

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