Microstructure and fracture toughness properties of CMT repairing welded 7075-T651 MIG welding joint

Bangjian Yang1, Zhenghong Fu1, Ting Li1, Meile Shan1, Kang Guo1, Bing Chen1, Wei Lu1, Guoqing Gou1 and Wei Gao2

1 Key Laboratory of Advanced Technology of Materials, Ministry of Education, Southwest Jiaotong University, Chengdu 610031, People’s Republic of China
2 Department of Chemical and Materials Engineering, The University of Auckland, PB 92019, Auckland 1142, New Zealand

E-mail: gouguoqing1001@163.com

Keywords: 7075-T651 aluminum alloy, cold metal transfer, repair welding, fracture toughness

Abstract

The cold metal transfer (CMT) technique was introduced to repair the heat-affected zone (HAZ) of the 7075-T651 aluminium (Al) alloy MIG welding joint using wire ER5356 as filler. The microstructural characteristics and fracture toughness of the welded joint before and after CMT repair welding was investigated. The results indicated that the sound welded joint was successfully produced through CMT; the repaired heat-affected zone (RHAZ) exhibited fine grain and small grain boundary precipitates (η phase) with a larger inter-particle spacing distance compared to that of the HAZ. Additionally, the J0 integral value of the RHAZ (43.38 KJ m⁻²) and the repaired weld metal (42.68 KJ m⁻²) were higher than that of the HAZ of the MIG welded joint (32.88 KJ m⁻²) and the CMT welded joint (32.81 KJ m⁻²). The fracture toughness properties of the joint repaired with CMT were improved without sacrificing its overall fracture toughness properties. This study proposes a new method for repairing MIG welding joints made of 7075-T651 Al alloy, further reducing the cost of manufacturing high-speed train.

1. Introduction

The 7075-T651 (Al-Zn-Mg-Cu system) high strength aluminium alloy has been recognized as a very promising key lightweight structural components due to low density and high specific strength: it sees wide use in the transportation industry, especially in high-speed trains [1, 2]. The metal-inert gas (MIG) welding process is the main method currently used for manufacturing high-speed trains car bodies, due to its faster automatic welding speed and higher productivity [3, 4]. Unfortunately, traditional MIG fusion welding may result in metallurgical defects, such as hot cracks and lack of fusion in joints due to high heat input [5, 6]. The heat-affected zone (HAZ) usually becomes the weakest and most hazardous region. In addition, cracks often appear in the HAZ of welded joints during the actual servicing of high-speed trains. Thus, the demand for repairing these defects has increased to ensure structural safety and a reduction in material consumption. Repair welding would be an effective way to fix these drawbacks. Studies by Akyel et al [7] have demonstrated that repair welding can be convenient, sustainable, less energy consumption and less manufacturing costs. Besides, suitably repaired welded components would have the same fracture toughness, ductility, and static strength as the parent structures reported by Salami et al [8].

Recently, an innovative cold metal transfer (CMT) welding technique has emerged for welding parts of aluminium alloy due to its low thermal input, excellent gap bridging ability and high energy efficiency [9, 10]. The significant characteristic of the CMT technique is that it utilizes an inventive wire feed system coupled with high speed digital controls to restrain material deposition and maintain its low thermal energy input [11]. Several studies have found that CMT is a preferred candidate for joining 7075 difficult to weld Al alloy. For instance, Gandhi et al [12] investigated a double-butt AA7075 alloy joint welded by CMT process, reporting that CMT averted the formation of coarse grains, resulting in a high-strength joint. Additionally, CMT minimised
welding defects such as detrimental oxide and porosity. Elrefaey [13] studied the 7075-T6 Al alloy joints welded by the CMT process, producing a defect-free joint with no cracks or spattering and few porosities. In addition, Elrefaey revealed that the CMT welding technique could fabricate welding joints with better mechanical performance than the traditional TIG and MIG processes, comparable to the LBW and FSW processes. Pfeifer and Rykala [14] compared the 7075-aluminium alloy butt joint welded by the MIG pulse and CMT processes. The ‘circle path’ tests revealed that the use of the CMT method reduced the formation of liquation hot cracks. Moreover, the bend tests revealed that joints welded with the CMT method had the highest plastic properties. They further concluded that the CMT method yielded higher quality welded joints with the aluminium alloy. Therefore, it would be attractive to explore repairing defective 7075-T651 Al alloy joints using the CMT welding process.

Furthermore, many cases of failure analysis in our laboratory showed that the 7xxx series Al alloy required not only high strength but also high toughness to be used for the load-carrying structures of high-speed trains [15-18]. Up till now, however, few studies have examined the fracture toughness of MIG welded joint made of 7075-T651 Al alloy repaired by the CMT process.

Therefore, in this work, we attempt to repair the hypothetical crack in the HAZ of the MIG welded joint made of 7075-T651 Al alloy through the CMT welding technique. Moreover, a similar U-shape groove in the weld toe is designed to remove discontinuities at the weld toe and reshape the weld bead, which is beneficial to create a smooth transition between the weld metal (WM) and the base metal (BM) and ultimately reduce stress concentration. The fracture toughness properties of the HAZ, the WM, the repair weld metal (RWM), the repaired heat-affected zone (RHAZ), and the BM before and after repair welding are evaluated through a three-point bend test with J integral method. Additionally, the influence of precipitated phase on the fracture toughness of the HAZ/RHAZ is explored. We hope this work will provide a foundation for experiments related to the CMT repair of 7xxx series Al alloy welded joints.

2. Materials and experiment

2.1. Welding procedure

A commercial 7075-T651 Al alloy plate of 12 mm thickness was the raw material. ER5356 welding wires with 1.2 mm diameter was used as the filling metal. Table 1 shows the detailed chemical compositions of the 7075-T651 Al alloy and ER5356 welding wire.

In the present study, first, 7075-T651 Al alloy butt joint configuration (figure 1(a)) was welded with three-layer welding through the metal inert gas (MIG; Fronius TransPlus Synergic 4000) technique; table 2 lists the welding parameters. Then the cold metal transfer (CMT; Fronius TransPlus Synergic 4000 CMT) technique was carried out to repair the weld toe of the 7075-T651 Al alloy butt joint through two-layer welding. Figure 1(b) and table 3 illustrate the schematic diagram and welding parameters of the repair welding of the 7075-T651 Al alloy, respectively. Before welding, we used a stainless-steel brush to eliminate the oxide layer on the surface of the 7075-T651 Al alloy.

2.2. Characterization methods

Optical microscopy (OM; ZEISS Axio observer A1m) was applied for analyzing the microstructure of the specimens. Specimens used for OM observations was fabricated by a three-step approach. First, specimens were ground by different meshes SiC paper from 200 to 1 500 grade, then polished until there were no scratches on the surface, finally etched by Keller’s reagent (HF: HCl: HNO₃: H₂O = 1: 1.5: 2.5: 95) at room temperature, the etching time limited in 30 ~ 45 s. The fracture surface analysis of the three-point bend specimens was performed by using scanning electron microscopy (SEM; FEI QUANTA FEG 250), operated at 20 KV. Transmission electron microscopy (TEM; FEI Tecnai G2 F30) was used to study the precipitation distribution and performed with an accelerating voltage of 300 KV. The TEM foil was prepared by using the precision ion polishing system (PIPS; Gatan Model 691). Specimens for TEM analysis, first, were mechanically thinned down to 80 ~ 100 μm thickness. Then, continuously thinned down to approximately 100 nm thickness by PIPS. Finally, punched into 3 mm diameter disks from slices.

| Table 1. Chemical compositions of 7075-T651 Al alloy and ER5356 welding wire (wt%). |
|---|---|---|---|---|---|---|---|---|
| Materials | Zn | Mg | Cu | Mn | Cr | Fe | Si | Al |
| 7075-T651 | 5.1 ~ 6.1 | 2.1 ~ 2.9 | 1.2 ~ 2.0 | 0.30 | 0.18 ~ 0.28 | 0.50 | 0.40 | Bal. |
| ER5356 | 0.10 | 4.5 ~ 5.5 | 0.10 | 0.05 ~ 0.20 | 0.05 ~ 0.20 | 0.40 | 0.25 | Bal. |
2.3. Hardness distribution measurement
The hardness tests were measured on a cross-sectional welded joint by using Vickers micro-hardness tester (HVS-30). The applied loading force was 5 Kgf and a holding time of 15 s. Hardness test working line from the cross-sectional top surface of specimen was 3 mm and the distance spacing between each indentation was 1 mm.

2.4. Fracture toughness test
Fracture toughness properties test was conducted on an electronic universal testing machine (SUST CMT4304) with a loading rate of 2 mm/min at room temperature. Pre-cracks were prepared by employing a cyclic deformation process. The details have been reported in our previous studies [17, 18]. Figure 1(c) presents the position-selected specimens for a three-point bend in the T-L orientation. In this study, the fracture toughness value of joints was obtained through the $J$ integral method. $J_0$ is calculated from the following equations (1) and (2), according to the standard ISO 12135:2016 (E).

$$J_0 = \frac{FS}{(BBN)^{0.5} W^{1.5} E} \left( \frac{a_0}{W} \right)^2 \times \frac{1 - \nu^2}{E} + \frac{\eta_p \Delta p}{B_N (W - a_0)}$$  

$$\eta_p = 3.667 - 2.119 \left( \frac{a_0}{W} \right) + 0.437 \left( \frac{a_0}{W} \right)^2$$

where $J_0$ is the uncorrected experimental equivalent to $J$ integral in KJ/m$^2$, $F$ is the applied force in KN, $B$ is the thickness of specimen in mm, $S$ is the bend span in mm, $B_N$ is the net thickness between side grooves of specimen in mm, $W$ is the width of test specimen, $a_0$ is the initial crack length in mm, $g_1 \left( \frac{a_0}{W} \right)$ is the stress intensity factor coefficient, $E$ is the modulus of elasticity in GPa, $\nu$ is the Poisson’s ratio, $\Delta p$ is the plastic component of area under plot of force $F$ versus specimen notch open displacement $V$ at the load-line in $J$. 

---

Table 2. MIG welding process parameters.

| Weld bead | Wire diameter (mm) | Welding torch tile angles (°) | Stick out (mm) | Shielded gas | Gas flow rate (L/min) | Welding speed (mm/s) | Wire feed speed (m/min) | Oscillating amplitude (mm) |
|-----------|--------------------|-----------------------------|----------------|--------------|----------------------|----------------------|------------------------|---------------------------|
| 1         | 1.2                | 80                          | 15             | 99.999% Ar   | 25                   | 6.5                  | 12                     | 2                         |
| 2         |                    |                             |                |              | 6.5                  | 13                   | 6                      |                           |
| 3         |                    |                             |                |              | 6.5                  | 14                   | 12                     |                           |

Figure 1. Schematic diagrams of welding procedure (unit: mm): (a) original weld by MIG welding, (b) repair weld by CMT, (c) specimen location selected for a three-point bend test.
| Weld bead | Wire diameter (mm) | Welding torch tile angles (°) | Stick out (mm) | Shielded gas | Gas flow rate (L/min) | Welding speed (mm/s) | Wire feed speed (m/min) | Oscillating amplitude (mm) |
|-----------|-------------------|------------------------------|----------------|--------------|----------------------|----------------------|------------------------|--------------------------|
| 1         | 1.2               | 75                           | 15             | 99.999% Ar   | 25                   | 4                    | 9                      | 0                        |
| 2         |                   | 69                           | 0              |              |                      |                      |                        |                          |
3. Results and discussion

3.1. Microstructures

Figure 2 illustrates the representative microstructure of different zones in the 7075-T651 Al alloy joint welded by MIG and repaired through the CMT process.

Obviously, original weld by MIG and repair weld by CMT (figure 2(a)) are both full of penetration, no cracks or lack of fusion are found, proving that CMT repair welding can produce sound joints. Additionally, the cross-sectional appearance of the weld is aesthetic and shows a smooth transition at the weld toe, confirming that the similar U-shape groove design is reasonable. As shown in figures 2(c) and (d), the microstructure of the WM and RWM in the weld center both exhibit a typical casting equiaxed dendritic structure, caused by heterogeneous nucleation and constitutional supercooling during rapid heating and cooling in molten pool metal [19]. Figures 2(b) and (e) present the transition zone (from the weld metal to the base metal) of the original weld and repair weld, respectively. The transition zone includes three zones: fusion zone (FZ), the partially melted zone (PMZ), and the HAZ/RHAZ. The FZ shows the columnar grain structure near the weld metal and an equiaxed dendritic network close to the HAZ/RHAZ, which has been found in the previous studies as well [20, 21]. The formation of the FZ is primarily related to melting and resolidification during the welding process. Moreover, partial melting of the grain boundaries in the FZ will occur due to the low-melting eutectic compound distributed continuously on the grain boundaries [4, 22]. In the FZ, the formation of the weld metal depends chiefly on the solidification conditions, including the solidification growth rate, the temperature gradient, and the diffusion effect. Partial fine recrystallized grains in the HAZ/RHAZ are clearly observed. In this zone, grain structure is determined by two types of solid state reactions: (a) under high temperature condition, the grains become coarse, and the precipitations dissolve, (b) under low temperature condition, the precipitations dissolve partially while transforming from a metastable phase to a stable phase. The PMZ exhibits a typical coarse columnar grain between the FZ and the HAZ/RHAZ. Furthermore, the incipient melting at the grain boundaries is observed, attributed to the wide freezing range of the 7075 Al alloy. The results obtained in this research are consistent with studies reported by Sevim et al [20] and Temmar et al [23]. The microstructure of the BM shows a fibrous structure along the rolling direction as presented in figure 2(f). In addition, the round black dots with different sizes are observed. According to the results given by Sivaraj et al [24], these dots could be insoluble second phase precipitates dispersed in various locations of the elongated grain.

The HAZ/RHAZ undergoes a thermal cycle that involves being heated to a high temperature and then rapidly cooled during the MIG and CMT processes. The thermal cycle divides into high temperature zones and low temperature zones. For 7075-T651 Al alloy, the generally accepted precipitation sequence follows below pattern [25]: SSSS (supersaturated solid solution) → GP zone → metastable η′ phase (MgZn2) → equilibrium η phase (MgZn3). The dissolution of precipitates will occur in the range of 50 ~ 150 °C for GP zone, 200 ~ 250 °C for η′ phase precipitates, and 300 ~ 350 °C for η phase precipitates at high heating rates and high temperatures [26]. The GP zone and the transition phase (η′), in the form of semi-coherent precipitates, are primarily responsible for hardening of the alloys [27]. In contrast, metastable precipitates (η′) may be replaced by

Figure 2. OM images of the 7075-T651 Al alloy joint: (a) original weld by MIG and repair weld by CMT, (b) the HAZ, (c) the WM, (d) the RWM, (e) the RHAZ, (f) the BM.
more equilibrium $\eta$ phases at low heating rates and low temperatures [28]. Meanwhile, in the low temperature zones, the GP zone and transition $\eta'$ phase near the grain boundary will precipitate an $\eta$ phase at the grain boundary [23, 26]. Figure 3 presents the morphology and distribution of the precipitates in the HAZ/RHAZ through TEM technology. The precipitates located along the grain boundary in the HAZ are coarse and distributed continuously. Serval relevant studies have indicated that the grain boundary precipitates are MgZn$_2$ [18, 29]. Conversely, the grain boundary precipitates in the RHAZ are decorated with the small and discontinuously distributed particles. Qin et al [16] determined that the fracture toughness of the Al-Zn-Mg alloy is largely dependent on the grain boundary precipitation ($\eta$ phase). The precipitates in the matrix of the RHAZ show a relatively uniform granular dispersion distribution, and the quantity of the intragranular precipitates is greater than that of the HAZ. Additionally, the spacing between precipitates in the RHAZ is larger than that in the HAZ.

3.2. Microhardness

Figure 4 displays the microhardness distributions of a cross-sectional 7075-T651 Al alloy joint welded by the MIG method and repaired through the CMT method.

The WM/RWM exhibits the lowest hardness value. Previous researchers have reported that a low number of alloying elements in the weld metal can decrease hardness [13, 30]. The Mg and Zn strengthening and alloying elements evaporate quickly during welding, causing a reduction of content in the weld metal. Additionally, the filler metal (ER5356) dilution effect can lead to element variation as well. Softening phenomenon obviously takes place in the HAZ/RHAZ due to the modification of precipitates [31]. A higher heat input produces a larger softened region and decreases overall hardness. The width of the RHAZ (∼6 mm) is narrower than that of the HAZ (∼11 mm), attributed to the CMT with lower heat input energy, the zone influenced by heating is smaller than that of MIG welding. Yan et al [29, 32] also confirmed that MIG welding spent much more thermal energy.
to melt a plate of the same thickness, causing a wider HAZ. The 7075-T651 BM has the highest hardness value due to the unaffected T6 temper treatment.

3.3. Fracture toughness properties
Fracture toughness is a key indicator of crack-contained materials’ resistance to instability propagation [33]. Figure 5 displays the $J_{0}$ integral value distribution of the HAZ, the WM, the RWM, the RHAZ and the BM.

After repair welding through the CMT technique, the average $J_{0}$ integral value of the RWM (42.68 KJ m$^{-2}$) and the RHAZ (43.38 KJ m$^{-2}$) increases by $\sim$30% compared with the HAZ (32.88 KJ m$^{-2}$ in MIG, 32.81 KJ m$^{-2}$ in CMT). The $J_{0}$ integral value does not change significantly in the HAZ after repair by CMT. The results indicate that the incorporation of CMT technology to repair 7075 Al alloy MIG welding joints does not rapidly sacrifice the overall fracture toughness of the joint. Most importantly, the $J_{0}$ integral value of the RHAZ improves; consequently, the ability of the RHAZ to resist crack propagation grows, proving that the CMT repair method is effective. The $J_{0}$ integral value of the HAZ/RHAZ has undergone significant changes, mainly related to the difference in the precipitates on the grain boundary. As shown in figure 3(b), the small size and large interparticle distance of the precipitates on the grain boundary are beneficial to the fracture toughness, in accordance with the previous studies [34, 35]. Moreover, Kawabata and Izumi [36] have reported that the fracture strain is given as follows:

$$\varepsilon_f \approx \frac{q}{k} \frac{w}{k'} D N$$

where $q$ is a factor in relation to the strain ratio of the interior of PFZ’s to that of grains, $k$ and $k'$ are the constant, $w$ is the width of the PFZ, $D$ is the size of grain boundary precipitate, $N$ is the number of grain boundary precipitates per unit area. According to equation (3), the coarse and continuous precipitates located on the grain boundary may cause degradation of the fracture toughness. In addition, grain boundary precipitates, especially continuous network precipitates, have severe embrittlement effect and can cause initial cracks, reducing fracture toughness. Conversely, grain boundary precipitates with finer size and increased interparticle spacing, dislocations may easily pass between particles, and stress concentration is less likely to occur, thus the fracture toughness is improved [37–39]. Based on the reasons mentioned above, the fracture toughness of the RHAZ is greater than that of the HAZ.

Fractographic examinations on the fracture surfaces of the broken specimens from a three-point bend test was performed with SEM. Figure 6 shows the fracture surface morphology of the crack propagation zone in the HAZ, the RHAZ, the RWM, and the BM.

The HAZ, which belongs to the quasi-cleavage fracture mode, displays river patterns, tearing edges, and fewer small dimples. Compared with the HAZ, the RHAZ has larger and more numerous dimples; the dimples are also deeper, and the fracture toughness of the RHAZ is improved. According to the previous study [40], deeper and larger dimples, the toughness would be better. The surface morphology of the RWM exhibits many
finer shallow dimples and uniform distribution, in keeping with transgranular ductile fracture mode. The fracture surface of the BM has more approximately equiaxed dimples than the three mentioned above. The BM possess the typical transgranular ductile fracture mode, in which the dimples are bigger and deeper. When the dimples are predominant, resistance against crack growth is much better [24], further confirming the superior fracture toughness of the BM.

4. Conclusion

In conclusion, CMT welding technique as repair process for the HAZ of 7075-T651 Al alloy MIG welded joints was reported. The fracture toughness properties of different zones in joints before and after CMT repair were measured by a three-point bend test through the J integral method. The results revealed that after CMT repair, the J Integral value of the RHAZ increased compared to the HAZ, and the ability to resist cracking propagation also improved. Meanwhile, CMT repair welding did not weaken the whole fracture toughness significantly compared with the MIG-welded joints. These findings seem to give us new inspiration and guidelines for repairing the 7075 Al alloy welded components used in high-speed trains with the CMT technique.

Acknowledgments

This work was financially supported by the Science & Technology Department of Sichuan Province (Grant No. 2018HH0139).

ORCID iDs

Guoqing Gou @ https://orcid.org/0000-0003-1559-3059

References

[1] Azarniya A, Taheri A K and Taheri K K 2019 Recent advances in ageing of 7xxx series aluminium alloys: a physical metallurgy perspective J. Alloys Compd. 781 945
[2] Dursun T and Soutis C 2014 Recent developments in advanced aircraft aluminium alloys Mater. Des. 56 862

[3] Mathers G 2002 The Welding of Aluminium and its Alloys (Sawston, Cambridge, England: Woodhead Publishing)

[4] Wang Y R and Chen H 2012 Welding Technology of Aluminium Alloy Train Body for High Speed Trains (Chengdu, Sichuan, China: Southwest Jiaotong University Publishing)

[5] Alatorre N, Ambriz R R, Amrouche A, Garcia C and Jaramillo D 2017 Fatigue crack growth in Al-Zn-Mg(7075-T651) welds obtained by modified indirect and gas metal arc welding techniques J. Mater. Process. Technol. 248 207

[6] Alatorre N, Ambriz R R, Noureddine B, Amrouche A, Talha A and Jaramillo D 2014 Tensile properties and fusion zone hardening for GMAW and MIG welds of a 7075-T651 aluminium alloy Acta Metall. Sin.-Engl. 27 694

[7] Ayké A, Kolstein M H and Bijlaard F S K 2018 Fatigue strength of repaired welds connections made of very high strength steels Eng. Struct. 161 28

[8] Salami P, Khandani T, Asadi P and Besharati M K 2014 Friction stir welding/processing as a repair welding Advances in Friction-Stir Welding and Processing 10 427

[9] Selvi S, Vishvakarsan A and Rajasekhar E 2018 Cold metal transfer (CMT) technology—an overview Defence Technol. 14 28

[10] Madhavan S, Kamaraj M and Vijayaraghavan L 2016 Cold metal transfer welding of aluminium to magnesium: microstructure and mechanical properties Sci. Technol. Weld. Join. 21 310

[11] Pickin G C and Young K 2013 Evaluation of cold metal transfer (CMT) process for welding aluminium alloy Sci. Technol. Weld. Join. 18 1183

[12] Gandhi C, Dixit N, Aranke O, Arivarasan M, Siva S N, Manikandan M and Arivazhagan N 2018 Characterization of AA7075 weldment using CMT process Materials Today: Proceedings 5 24024

[13] Elrefaey A 2015 Effectiveness of cold metal transfer process for welding 7075 aluminium alloys Sci. Technol. Weld. Join. 20 280

[14] Pfeifer T and Rykala J 2014 Welding EN AW 7075 aluminium alloy sheets J. Mater. Process. Technol. 214 99

[15] Yan X Y, Chen H, Wang Q Y and Zhu Z T 2016 Micro-zone performance of A7N01P-T4 aluminium alloy laser-MIG composite welding joint Trans. China Weld. Inst. 37 144 http://bjjh.cnjournals.net/zh/reader/view_abstract.aspx?file_no=20160827&flag=1

[16] Qin C, Gou G Q, Che X L, Chen H, Chen J, Li P and Gao W 2016 Effect of composition on tensile properties and fracture toughness of Al–Zn–Mg alloy (A7N01S-T5) used in high speed trains Mater. Des. 91 278

[17] Li B, Wang X M, Chen H, Hu J, Huang C and Gou G Q 2016 Influence of heat treatment on the strength and fracture toughness of 7N01 aluminium alloy J. Alloy Compd. 676 160

[18] Gou G Q, Chen J, Wang Z R, Chen H, Ma C P and Li P 2016 Stress corrosion cracking behavior of 4.19%Zn-1.34%Mg aluminium alloy welded joints Corrosion Science 123 1133

[19] Pujari K S, Patil D V and Mewandi G 2014 Selection of GTAW process parameter and optimizing the weld pool geometry for AA 7075-T6 aluminium alloy Materials Today: Proceedings 5 25045

[20] Sevim I, Hayat F, Kaya Y, Kahraman N and Sahin S 2013 The study of Mg weldability of heat-treated aluminium alloys Int. J. Adv. Manuf. Tech. 66 1825

[21] Zucchi F, Trabannelli G and Grassi V 2001 Pitting and stress corrosion cracking resistance of friction stir welded AA 5083 Mater. Corros. 52 835

[22] Kou S 2003 Welding Metallurgy (Hoboken, New Jersey: John Wiley & Sons Publishing)

[23] Temmar M, Hadji M and Sfaraouli T 2011 Effect of post-weld aging treatment on mechanical properties of tungsten inert gas welded low thickness 7075 aluminium alloy joints Mater. Des. 32 3552

[24] Sivaraj P, Kanagarajan D and Balasubramaniam V 2014 Fatigue crack growth behaviour of friction stir welded AA7075-T651 aluminium alloy joints T. Nonferr. Metal Soc. 24 2459

[25] Leng L, Zhang Z J, Duan Q Q, Zhang P and Zhang Z F 2018 Improving the fatigue strength of 7075 alloy through aging Mater. Sci. Eng. A 734 724

[26] Huang S, Xu L, Chen H, Che X, Wang Y and Yang X 2019 Effect of laser repairing on corrosion behaviour of metal-inert gas welding joint of 7071 aluminium alloy Mater. Corros. 70 1578–1592

[27] Fu G, Tian F and Wang H 2006 Studies on softening of heat-affected zone of pulsed-current GMA weld Al-Zn-Mg alloy J. Mater. Process. Technol. 180 216

[28] Ringer S P and Honk K 2000 Microstructural evolution and aging behaviour in aluminium alloys: atom probe field-ion microscopy and transmission electron microscopy studies Mater. Character. 44 101

[29] Yan S H, Chen H, Zhu Z T and Gou G Q 2014 Hybrid laser-metal inert gas welding of Al–Mg–Si alloy joints: microstructure and mechanical properties Mater. Des. 61 160

[30] Wu S C, Yu X, Zuo R Z, Zhang W H, Xie H L and Jiang J Z 2013 Porosity, element loss, and strength model on softening behavior of hybrid laser arc welded Al-Zn-Mg-Cu Alloy with synchrotron radiation analysis Weld. J. 92 64 http://ir.sinap.ac.cn/handle/331007/53857

[31] Ma T and Den O G 1999 Softening behaviour of Al–Zn–Mg alloys due to welding Mater. Sci. Eng. A 266 198

[32] Yan S H, Nie Y, Zhu Z T, Chen H, Gou G Q, Xu J P and Wang G G 2014 Characteristics of microstructure and fatigue resistance of hybrid fibre laser-MIG welded Al-Mg alloy joints Appl. Surf. Sci. 298 12

[33] Li H F, Duan Q Q, Zhang P, Zhou X H, Wang B and Zhang Z F 2019 The quantitative relationship between fracture toughness and impact toughness in high-strength steels Eng. Fract. Mech. 211 362

[34] Wang D, Ni D R and Ma Z Y 2008 Effect of pre-strain and two-step aging on microstructure and stress corrosion cracking of 7050 alloy Mater. Sci. Eng. A 494 360

[35] Dumont D, Deschamps A and Brechet Y 2003 On the relationship between microstructure, strength and toughness in AA7050 aluminium alloy Mater. Sci. Eng. A 356 326

[36] Kawabata T and Isumi O 1976 Ductile fracture in the interior of precipitate free zone in an Al-6.0%Zn-2.6%Mg alloy Acta Metall. 24 817

[37] Kawabata T and Isumi O 1977 The relationship between fracture toughness and transgranular fracture in an Al-6.0%Zn-2.5%Mg alloy Acta Metall. 25 505

[38] Hahn G T and Rosenfield A R 1975 Metallurgical factors affecting fracture toughness of aluminium alloys Metall. Trans. 6 1653

[39] Hornbogen E and Graf M 1977 Fracture toughness of precipitation hardened alloys containing narrow soft zones at grain boundaries Acta Metall. 25 877

[40] Li D, Yang X, Cui L, He F and Zhang X 2015 Investigation of stationary shoulder friction stir welding of aluminium alloy 7075–T651 J. Mater. Process. Technol. 222 391