Weldability of A7075-T651 and AZ31B dissimilar alloys by MIG welding method based on welding appearances

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Abstract. It is not recommended to weld aluminium and magnesium dissimilar alloys using fusion welding method because of the formation of AlₘMgₙ type intermetallic brittle compounds like Mg₃Al₃, Mg₁₇Al₁₂ etc. in the welding joint. These brittle compounds deteriorate the mechanical properties of the joint. But so far, insufficient researches have been attempted to stop the formation of AlₘMgₙ type intermetallic brittle compounds in fusion welding method. The aim of this research work was to investigate on the weldability between A7075-T651 and AZ31B dissimilar alloys based on welding appearances and study the formation of intermetallic brittle compounds at the joint. In this research, A7075-T651 and AZ31B alloys were welded using ER5356 filler wire in MIG welding method in butt configuration. 100% argon was used as shielding gas. The results showed that, most of the welding appearances were moderate. The macroscopic investigation at all welding cross section showed that a lot of AlₘMgₙ intermetallic brittle compounds were formed at the interface between weld seam and AZ31B parent metal side which caused macro cracks. A good number of macro pores were also observed at AZ31B parent metal side. These cracks and pores could easily cause the failure of the joint at very low stress.

1. Introduction
Innovative developments in dissimilar welding technologies for light weight alloys of aluminum (Al) and magnesium (Mg) would achieve weight reduction, enhance quality of components and increase fuel efficiency in automobile, marine, aviation and aerospace industries to reduce the environmental pollution. So, importance of lightweight dissimilar metal welding between Al and Mg alloys is crucial in transportation industries [1, 2]. Liu et al. stated that the welding of Mg alloy to Al alloy would improve flexibility and availability of components substantially [3].

Recently, in many industrial fields, much attention has been focused on Al and Mg alloys because not only for the above reasons but also for their various unique properties. For their realistic applications, welding technologies should be established in addition to consider issues such as alloy design, microstructure control and surface treatment [4].

Al is one of the most important industrial nonferrous metals. Al alloys are extensively used in automotive, aerospace, ship and electronic industries and communication equipment as structural material [5] because of their attractive mechanical and metallurgical properties like high specific strength, light weight, durability, low-cost maintenance [6], recovery potential, good formability,
weldability, good corrosion resistance, good thermal and electrical conductivity [7], recyclability [8] etc. Magnesium, the lightest of all structural metals are also attractive, promising and has great potential in these manufacturing fields. Mg, with density two-thirds of Al alloy, has highest specific strength [6, 9], good cast ability, workability and electromagnetic shielding capability. These Al and Mg alloys have been researched extensively for practical industrial applications during the past decade. But it has been found that the process of joining Al and Mg is a very complicated one because of difference in physicochemical properties, occurrence of cracking in the joint [10] and reactions between Al and Mg atoms can yield extremely brittle intermetallic compounds specially in fusion welding process [9, 10]. So, in order to achieve further design flexibility, expanded combined structural applications [9] of the properties of Al and Mg alloys, development of reliable joints is the principal technical challenge. However to develop a reliable joining method, a variety of attempts to weld these alloys using conventional fusion welding technology showed that it is difficult to obtain sound dissimilar welds since coarse grains [1], Mg$_2$Al$_3$, Mg$_{17}$Al$_{12}$ etc. inter-metallic compounds near interface between two metals, which have a strong negative effect on the mechanical properties of the welding joints, are easy to form in these processes [2, 3, 5, 9, 11-15]. Thus, the problem of welding Al and Mg alloys needs to be solved to establish technologies to promote their use in industrial application. Not only in the traditional fusion welding but also even in high energy density laser welding with higher cooling rate[2], friction stir welding and laser-TIG hybrid welding processes, the detrimental intermetallic compounds could be formed easily and the joint performance could be deteriorated significantly. In additional, these methods need expensive equipment and complicated welding procedures.

So, to develop the solution in Al and Mg welding, the conventional fusion welding processes like MIG welding is very important[13]. MIG is a fusion welding method and it is easy, quick, efficient, economic, can produce very good quality welding and can be mechanized. Therefore, the aim of this research work was to investigate on the reliable ranges of welding parameters for a good welding appearance and to study the formation of Al$_m$Mg$_n$ type intermetallic brittle compounds at the welding joint cross section so that further research can be done to stop the formation brittle compound and thus better mechanical properties can be achieved.

2. Experimental

Commercially available 2 mm thick A7075-T651 Al and AZ31B Mg sheets were cut into 50×30 mm dimension. Then A7075-T651 sheets were welded to AZ31B sheets in butt configuration using 1mm diameter ER5356 filler wire by metal inert gas (MIG) welding method. 100% argon was used as shielding gas. The specimens were gripped by jig on an automatic welding table. The variable parameters were welding voltage $V$, welding current $I$, welding speed $WS$ and gun angle $GA$. The fixed parameters were tip length (10 mm) and gas Supply rate (25 Ltr./min).

The net Heat input, $H$ can be calculated from the equation 1 given below as the ratio of the total input power, $P$ of the heat source to its travel speed or welding speed, $v$.

$$H = \frac{P}{v}$$  \hspace{1cm} (1)

Where, $H$ is in watt-seconds or joules per mm or inch, $P$ in watts and $v$ in mm per second or inches per minute. For an electric arc, $P= VI$ where $V$ is volts and $I$ is current [16].

The design of experiment (DOE) for the variable parameters was done in Box-Behnken design by response surface methodology. The first round of DOE was done with variable parameter ranges: $V$ (10-25V), $I$ (65-130A), $WS$ (2-8 mm/s), $GA$ (45-90°) and welding was performed. Based on the welding appearances the revised DOE was done with adjusted variable parameter’s ranges: $V$ (12-15V), $I$ (55-60A), $WS$ (4-6 mm/s), $GA$ (45-90°) and welding was performed again. The two stages of DOE for variable parameters with ranges, heat inputs and quality of welding appearances are given in Table 1 and Table 2 respectively.
**Table 1:** First round design of experiment for variable parameters with ranges, heat inputs and quality of welding appearances

| Sl. | Welding Voltage, V (10-25 volts) | Welding Current, I (65-130A) | Welding Speed, WS v (2-8 mm/s) | Gun Angle, θ (45-90°) | Heat Input, H (Joules/mm) | Welding Appearances |
|-----|---------------------------------|------------------------------|--------------------------------|----------------------|--------------------------|---------------------|
| 1   | 10.0                            | 65.0                         | 2                              | 45.0                 | 325.00                   | Burns               |
| 2   | 25.0                            | 65.0                         | 2                              | 45.0                 | 812.50                   | Burns               |
| 3   | 10.0                            | 130.0                        | 2                              | 45.0                 | 650.00                   | Burns               |
| 4   | 25.0                            | 130.0                        | 2                              | 45.0                 | 1625.00                  | Burns               |
| 5   | 17.5                            | 97.5                         | 5                              | 45.0                 | 341.25                   | Burns               |
| 6   | 10.0                            | 65.0                         | 8                              | 45.0                 | 81.25                    | Poor                |
| 7   | 25.0                            | 65.0                         | 8                              | 45.0                 | 203.13                   | Burns               |
| 8   | 10.0                            | 130.0                        | 8                              | 45.0                 | 162.50                   | Moderate            |
| 9   | 25.0                            | 130.0                        | 8                              | 45.0                 | 406.25                   | Burns               |
| 10  | 17.5                            | 97.5                         | 2                              | 67.5                 | 853.13                   | Burns               |
| 11  | 17.5                            | 65.0                         | 5                              | 67.5                 | 227.50                   | Burns               |
| 12  | 10.0                            | 97.5                         | 5                              | 67.5                 | 195.00                   | Moderate            |
| 13  | 17.5                            | 97.5                         | 5                              | 67.5                 | 341.25                   | Burns               |
| 14  | 25.0                            | 97.5                         | 5                              | 67.5                 | 487.50                   | Burns               |
| 15  | 17.5                            | 130.0                        | 5                              | 67.5                 | 455.00                   | Burns               |
| 16  | 17.5                            | 97.5                         | 8                              | 67.5                 | 213.28                   | Burns               |
| 17  | 10.0                            | 65.0                         | 2                              | 90.0                 | 325.00                   | Burns               |
| 18  | 25.0                            | 65.0                         | 2                              | 90.0                 | 812.50                   | Burns               |
| 19  | 10.0                            | 130.0                        | 2                              | 90.0                 | 650.00                   | Burns               |
| 20  | 25.0                            | 130.0                        | 2                              | 90.0                 | 1625.00                  | Burns               |
| 21  | 17.5                            | 97.5                         | 5                              | 90.0                 | 341.25                   | Burns               |
| 22  | 10.0                            | 65.0                         | 8                              | 90.0                 | 81.25                    | Poor                |
| 23  | 25.0                            | 65.0                         | 8                              | 90.0                 | 203.12                   | Burns               |
| 24  | 10.0                            | 130.0                        | 8                              | 90.0                 | 162.50                   | Moderate            |
| 25  | 25.0                            | 130.0                        | 8                              | 90.0                 | 406.25                   | Burns               |

**Table 2:** Revised design of experiment with adjusted ranges of variable parameters, heat inputs and quality of welding appearances

| Sl. | Welding Voltage, V (12-15 volts) | Welding Current, I (55-60A) | Welding Speed, WS v (4-6 mm/s) | Gun Angle, θ (45-90°) | Heat Input, H (Joules/mm) | Welding Appearances |
|-----|---------------------------------|------------------------------|--------------------------------|----------------------|--------------------------|---------------------|
| 1   | 12.0                            | 55.0                         | 5                              | 67.5                 | 132.00                   | Good               |
| 2   | 15.0                            | 55.0                         | 5                              | 67.5                 | 165.00                   | Moderate            |
| 3   | 12.0                            | 60.0                         | 5                              | 67.5                 | 144.00                   | Moderate            |
| 4   | 15.0                            | 60.0                         | 5                              | 67.5                 | 180.00                   | Moderate            |
| 5   | 13.5                            | 57.5                         | 4                              | 45.0                 | 194.06                   | Moderate            |
| 6   | 13.5                            | 57.5                         | 6                              | 45.0                 | 129.38                   | Burnt              |
| 7   | 13.5                            | 57.5                         | 4                              | 90.0                 | 194.06                   | Moderate            |
| 8   | 13.5                            | 57.5                         | 6                              | 90.0                 | 129.38                   | Burnt              |
| 9   | 12.0                            | 57.5                         | 5                              | 45.0                 | 138.00                   | Moderate            |
| 10  | 15.0                            | 57.5                         | 5                              | 45.0                 | 172.50                   | Moderate            |
| 11  | 12.0                            | 57.5                         | 5                              | 90.0                 | 138.00                   | Moderate            |
| 12  | 15.0                            | 57.5                         | 5                              | 90.0                 | 172.50                   | Good               |
3. Results and discussions

3.1 Welding Appearances

The welding appearances for first round of DOE are shown in Figure 1 and it was revealed that between heat input 162.50 to 195.00 joules/mm, the welding appearances are moderate. Below this heat input range, the welding quality is poor as shown in Figure 2 and above this heat input range, the burning of the parent metal occurs as shown in Figure 3. The poor welding appearances were due to lack of fusion and burning occurred due to high heat input. So, the parameter ranges were adjusted so that the heat input could be maintained around the range of 162.50 to 195.00 joules/mm. For this purpose, the new ranges of welding variable parameters were set as: $V$ (12-15V), $I$ (55-60A), $WS$ (4-6 mm/s) and $GA$ (45-90°). Using the new DOE with adjusted variable parameters the welding was performed again. As shown in Figure 4 (a-y), most of the welding appearances were improved. Most of the welding joints showed moderate appearances. Three types of welding appearances were attained with new DOE for adjusted variable parameters: good, moderate and poor welding appearances. The acceptable quality welding appearances were rated as good; the medium quality welding appearances were rated as moderate. The welding where burning of the parent metals occurred were rated as poor welding appearances.

|    | $V$   | $I$   | $WS$ | $GA$ | Welding Appearance |
|----|-------|-------|------|------|-------------------|
| 13 | 13.5  | 55.0  | 4    | 67.5 | 185.63 Moderate   |
| 14 | 13.5  | 60.0  | 4    | 67.5 | 202.50 Moderate   |
| 15 | 13.5  | 55.0  | 6    | 67.5 | 123.75 Burnt      |
| 16 | 13.5  | 60.0  | 6    | 67.5 | 135.00 Moderate   |
| 17 | 12.0  | 57.5  | 4    | 67.5 | 172.50 Moderate   |
| 18 | 15.0  | 57.5  | 4    | 67.5 | 215.63 Moderate   |
| 19 | 12.0  | 57.5  | 6    | 67.5 | 115.00 Good       |
| 20 | 15.0  | 57.5  | 6    | 67.5 | 143.75 Moderate   |
| 21 | 13.5  | 55.0  | 5    | 45.0 | 148.50 Moderate   |
| 22 | 13.5  | 60.0  | 5    | 45.0 | 162.00 Moderate   |
| 23 | 13.5  | 55.0  | 5    | 90.0 | 148.50 Burnt      |
| 24 | 13.5  | 60.0  | 5    | 90.0 | 162.00 Burnt      |
| 25 | 13.5  | 57.5  | 5    | 67.5 | 155.25 Moderate   |

Figure 1: Moderate welding appearances (a) for exp. no 8 with heat input of 162.50 joules / mm and (b) for exp. no. 12 with heat input of 195.00 joules / mm

Figure 2: Poor welding appearances for exp. no 6 and 22 (for same heat input of 81.25 joules / mm)
Figure 3: Burning occurs in exp. no 4 and 20 (for same heat input of 1625.00 joules / mm)
Figure 4: Welding appearances for different heat input (for exp. no 1 to exp. no 25)

3.2 Macrostructure at welding cross section

Figure 5(a) shows the optical image at the welding cross section for one of the welding joints. The welding joint contained macro cracks at the interface of AZ31B and welding seam. No cracks were observed at the interface of A7075-T651 and welding seam. The top of welding seam contained a good number of macro pores. All the welding joints depicted the same scenario.
Figure 5: (a) Optical image of welding cross section showed the presence of macro cracks and macro pores, (b) Macrostructure of welding cross section showed the presence of Al$_m$Mg$_n$ intermetallic brittle compounds and macro pores.

Figure 5(b) shows the macrostructure at welding cross section for one of the welding joints. It revealed that, a lot of Al$_m$Mg$_n$ intermetallic brittle compounds were formed at the interface of AZ31B and welding seam. These brittle compounds are the reason for the formation of macro cracks. A good number of macro pores were also observed at AZ31B parent metal side. No Al$_m$Mg$_n$ intermetallic brittle compounds were observed at the interface of A7075-T651 and welding seam. The same thing happened for all the welding joints. Al$_m$Mg$_n$ intermetallic brittle compounds formed because aluminium based ER5356 filler wire was used for welding which reacted with AZ31B parent. This intermetallic brittle compound is the reason for poor mechanical properties of the joint reported by all previous researchers.

4. Conclusion

a. The variable parameters range for good and moderate welding appearances are: $V$ (12-15V), $I$ (55-60A), $WS$ (4-6 mm/s) and $GA$ (45-90°).

b. The formation of Al$_m$Mg$_n$ intermetallic brittle compounds were at the interface of AZ31B and welding seam which produced macro cracks. A good number of macro pores were also observed at AZ31B parent metal side and at the top of welding seam. The macro cracks at the interface of AZ31B and welding seam, and macro pores at AZ31B parent metal side would definitely cause poor mechanical properties of the joint which could cause failure at very low stress.

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