International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 11 (2017) pp. 2832-2839


# Metallurgical and Mechanical Properties of Heat Treatable Aluminum Alloy AA6082 Welds

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## Abstract

Heat treatable alloy AA6082 is a medium strength alloy with have excellent formability from simple to complex profiles by extrusion and good corrosion resistance characteristics. It is one of the most widely used alloys and has considerable industrial interest. These materials can be heat treated to produce precipitation to various degrees. Mg and Si are the major solutes they increase the strength of the alloy by precipitation hardening. This article presents a survey for the main work done concerning welding and heat treatment carried out to this alloy. Metallurgical and mechanical properties of the AA6082 similar and dissimilar welds were reviewed.

**Keywords:** Al-Mg-Si alloy, AA 6082, TIG, MIG, heat-treatable alloy, heat treatment, metallurgical properties, mechanical properties, similar welding, dissimilar welding.

## INTRODUCTION

Aluminum and its alloys are extensively utilized in many industries such as automotive, shipbuilding, aircraft, structural applications, appliances, food packaging and transportation industry [1-7] due to their high strength to weight ratio and corrosion resistance and for their attractive mechanical properties achieved by thermal treatments.

**Table 1.** Wrought aluminum alloy designation

| Alloying Element | Wrought |
|---|---|
| Non (99%+ Aluminum) | 1XXX |
| Copper | 2XXX |
| Manganese | 3XXX |
| Silicon | 4XXX |
| Magnesium | 5XXX |
| Magnesium + Silicon | 6XXX |
| Zinc | 7XXX |
| Lithium | 8XXX |

Copper, magnesium, zinc, manganese, lithium and silicon are commonly added to aluminum as alloying elements. Chromium, zirconium, titanium, lead, nickel and bismuth are also added as small additions. Aluminum alloys are either wrought or cast alloys. For wrought alloys, the designation contains 4 digits while in cast alloys fifth digit is added. **Table 1** shows the designation system for wrought alloys.

### Strength and Corrosion Resistance of Aluminum

Unalloyed aluminum has low strength. When adding alloying elements such as copper, silicon, manganese and magnesium the strength property increases to tailor particular applications. At cold environment, tensile strength of aluminum increases while retaining its toughness. This is an advantage over steel which loses its toughness to be brittle at low temperature.

Tensile strength of pure/unalloyed aluminum is around 90 MPa and can be increased to over 700 MPa for some heat-treatable alloys. Main methods to increase the aluminum strength are alloying, heat treatment and cold working. These methods are applied to pure aluminum to achieve the application requirements.

### Heat Treatment of Aluminum

There are various heat treatments which can be carried out for aluminum to increase its metallurgical and mechanical properties. These treatment methods can be briefly described as: *Homogenization, Annealing, Precipitation/Age Hardening and Solution Heat Treatment*. In the designation system a suffix will appear describing the heat treatment method. Namely; “**F**” for fabricated, “**O**” for annealed wrought products, “**T**” for heat treated, “**W**” for solution heat treatment and “**H**” for non-heat treatable alloys (3XXX, 4XXX & 5XXX) which can be cold worked or strain hardened.

## HEAT TREATABLE ALUMINUM ALLOY 6082

Aluminum–magnesium–silicon (Al–Mg–Si) denoted as 6XXX series alloys are medium strength heat treatable alloys and have excellent formability from simple to complex profiles by extrusion [8] and good corrosion resistance characteristics [5]. Mg and Si are the major solutes they increase the strength of the alloy by precipitation hardening. There has been a considerable industrial interest in these alloys because two-thirds of all extruded products are made of aluminum and 90% of those are made from 6XXX series alloys [9]. In this series, AA6082 is one of the most widely used alloys [10]. These materials can be heat treated to produce precipitation to various degrees.

**Table 2.** Chemical composition of aluminum alloy 6082

| Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Other elements | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | **Each** | **Total** |
| 0.7-1.3 | 0.5 | 0.10 | 0.4-1.0 | 0.6-1.2 | 0.25 | 0.20 | 0.1 | 0.05 | 0.15 |

Chemical and mechanical properties of aluminum alloy 6082 is summarize in **Table 2** and **Table 3**, respectively [11-13].

**Table 3.** Mechanical properties of aluminum alloy 6082

| Temper | Proof Stress 0.20% (MPa) | Tensile Strength (MPa) | Shear Strength (MPa) | Elongation A5 (%) | Elongation A50 (%) | Hardness Brinell HB | Hardness Vickers HV | Fatigue Endur. Limit (MPa) |
|---|---|---|---|---|---|---|---|---|
| **O** | 60 | 130 | 85 | 27 | 26 | 35 | 35 | 120 |
| **T1** | 170 | 260 | 155 | 24 | 24 | 70 | 75 | 200 |
| **T4** | 170 | 260 | 170 | 19 | 19 | 70 | 75 | 200 |
| **T5** | 275 | 325 | 195 | 11 | 11 | 90 | 95 | 210 |
| **T6** | 310 | 340 | 210 | 11 | 11 | 95 | 100 | 210 |

The T6 treatment involving solution heat treatment and subsequent artificial aging and quenching is a common method to increase the strength of the alloy [14, 15]. The solution heat treatment is first performed at 500°C to obtain the supersaturated $\alpha$ solid solution. Artificial aging is obtained by heating to about 200°C for various amounts of time and leads to precipitation of various phases (leading to the stable $\beta$ phase). The hardness and strength are determined by the precipitate type, density and size [16].

Precipitation hardening in Al-Mg-Si alloys with and without excess Si had been investigated [17]. Excess Si increases the effective amount of the hardening phases above ~ 0.9 wt.% Si and rate of strengthening increases until the overall Mg and Si ratio in the alloy is close to approximately 0.4. Dispersoid formation and recrystallization behavior in Al-Mg-Si-Mn had been studied and showed that the cold deformation influences the recrystallization and grain growth [18].

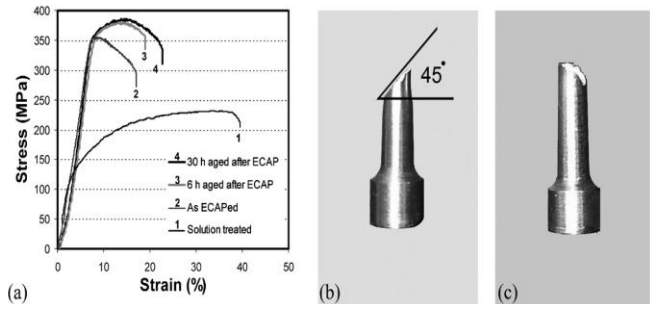



**Fig. 1 (a)** Tensile curves of post-ECAP aged specimens at 100C for 6 and 30 h (b) ruptured tensile specimen after ECAP, and (c) ruptured tensile specimen after ECAP-aging [19].

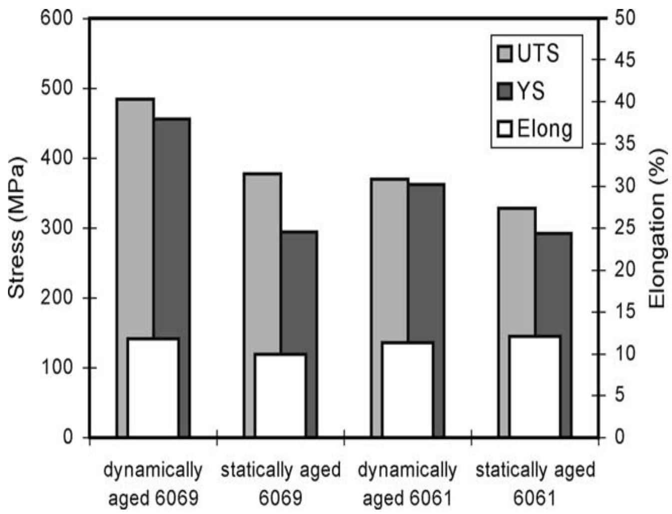



**Fig. 2** Tensile properties of the 6069 and 6061 alloys after dynamic ageing and static peak-ageing at 170C [20].

Aluminum alloy 6082 could be strengthen by combining aging treatment and ECAP process [19]. An increase in both strength and ductility of the ECAPed specimen was achieved via appropriate post-aging treatment as shown in **Fig. 1**. A comparison between static and dynamic aging using equal channel angular extrusion (ECAE) of two Al-Mg-Si alloys [20] showed dynamic aging is efficient in executing aging treatment that results in superior mechanical properties of this alloy Al-Mg-Si as shown in **Fig. 2**.

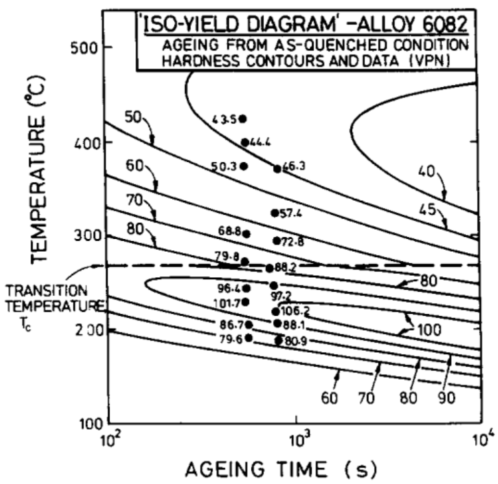
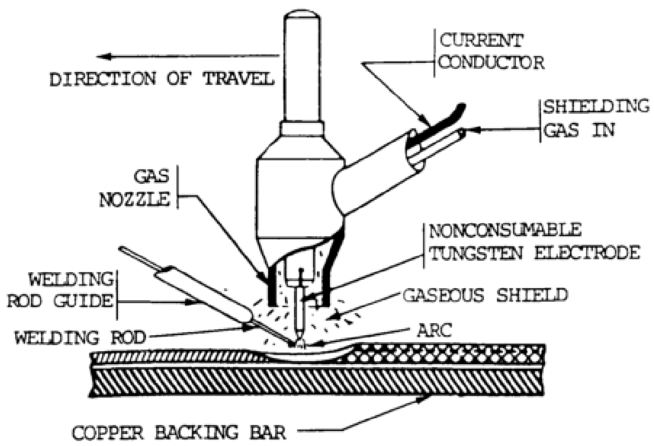



**Figure 3.** Data from ageing alloy 6082 from as-quenched condition compared with the model for both high and low temperature regimes [22].

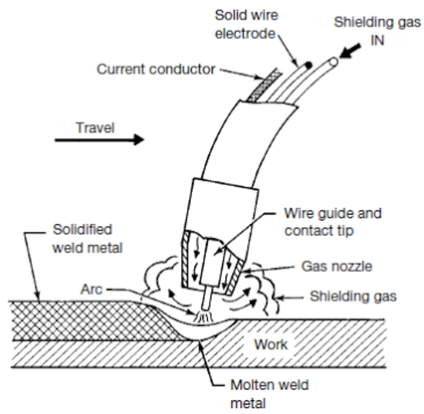
Age hardening of heat treatable aluminum alloys including 6082 was discussed and modelled [21]. The model is used to describe the change in yield strength due to age hardening. The model was applied to a number of heat treatments, establishing a basis for such problems as the prediction of the strength loss in the heat-affected zone of welds [22]. The data for aging alloy 6082 from as-quenched condition reduced to equivalent isothermal treatments, and compared with the model for both high and low temperature regimes is shown in **Fig. 3** [22].

## WELDING OF ALUMINUM ALLOY 6082

Aluminum and its weldable alloys are usually welded using fusion and non-fusion welding processes. Tungsten Inert-Gas (TIG) and Metal Inert-Gas (MIG) welding processes are preferred for aluminum welding because of their high quality welds. **Figure 4** shows schematic representation for both TIG and MIG welding processes.




**(a).** TIG welding




**(b)** MIG welding

**Figure 4.** Schematic representation for (a) TIG and (b) MIG welding processes.

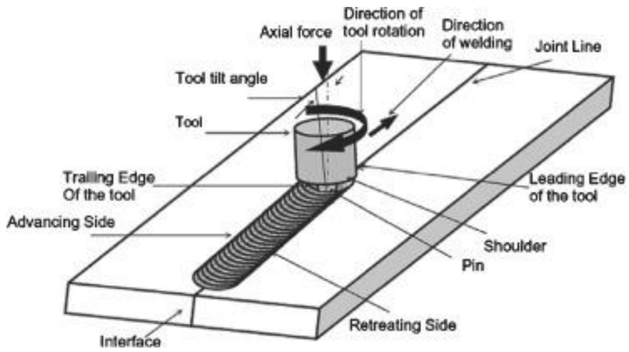



**Figure 5.** Friction stir welding (FSW) process.

Friction stir welding (FSW) process is used nowadays for welding metals in general especially aluminum alloys because of its simple and excellent weld quality it produces. The process is non-fusion welding process. The problems of fusion welding are eliminated with this process. Principals of FSW process is shown in **Fig. 5**.

### Metallurgical Characteristics of Welded AA6082

Fusion welding of aluminum alloy 6082 is widely applied in many applications but weldability problems do exist, namely, solidification cracking, liquation cracking, porosity and overaging of the heat affected zone (HAZ) [23-33]. The relatively high thermal expansion of Al-alloys is believed to be the main cause for the susceptibility of these alloys to weld cracking. Their large changes in volume upon freezing as well as their wide solidification temperature range [25-27]. This phenomenon dramatically decreases the mechanical properties of the welded joint. The same effect is observed due to the creation of a soft zone in the HAZ caused by overaging as a result of the thermal cycle imposed on the joint during welding [27]. The mechanical properties of the joint for the latter case can be recovered by postweld heat treating (solutionizing, quenching and aging) [34, 35]. Rapid quenching, however, can lead to distortion of the welded joint and, inconveniently, in many cases it might not be accessible for heat treating and it has to go on service in the as welded condition [36]. The microstructural changes that lead to loss of hardening and thereby mechanical strength in the HAZ of heat treatable aluminum alloys is a well-recognized issue that has to be taken into account when designing welded structural components [37].

The strength falls below the allowable limit specified by the standard. This is likely to be the result of the larger thermal affection due to the multi-passes procedure needed to fill the V groove butt joint. Although at high cost, this procedure can be suppressed by using the high concentration energy welding processes such as laser or electron beam [38-42].

Solidification crack sensitivity for aluminum alloy 6082-T6 was measured using Houldcroft test. TIG welding was applied. The weldability test showed high values of 44%. The selection of proper filler metal is important to lower this value. This investigation concluded that alloying with high amount of Mg (5%) can positively influence solidification cracking very much [43]. Crack susceptibility ratio for the 6082 alloy is shown in **Fig. 6**.

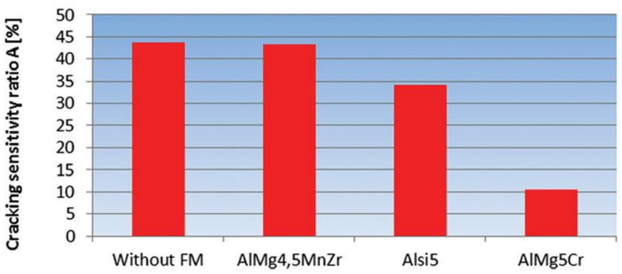
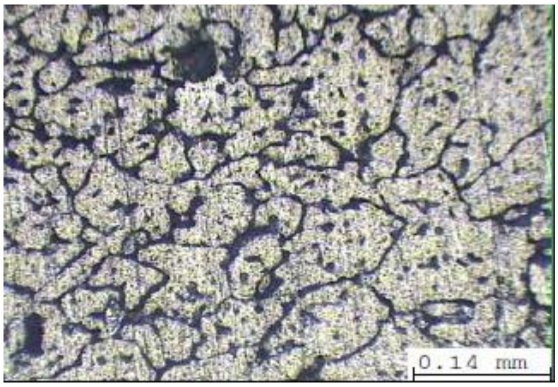
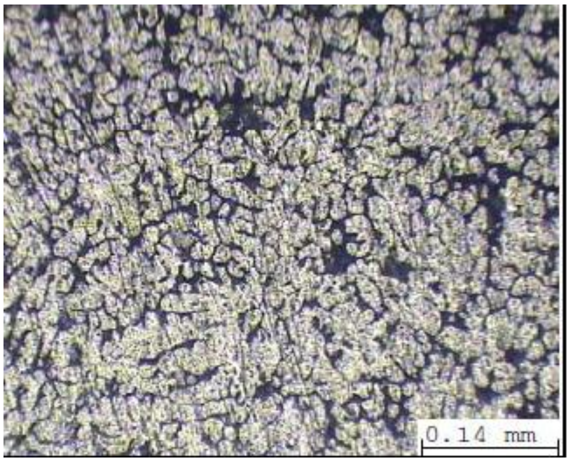



**Figure 6.** Cracking susceptibility ratio for TIG welded AA 6082, filler metal influence [43].

Microstructure and hardness of welded aluminum alloy 6082 were investigated under various current of TIG welding [44]. Using current of 140 ampere resulted in fine grain structure and uniform dimples. This enhanced tensile strength of the joint. Hardness increased with decreased current. **Figure 7** shows a comparison between microstructure of welded AA 6082 at 100A and 140A using TIG welding process [44].




**(a)**



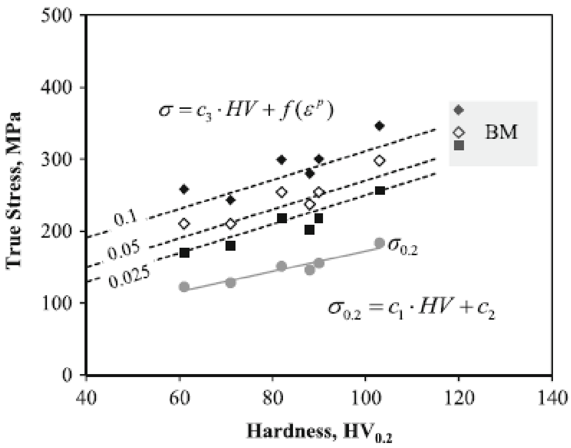

(b)

**Figure 7.** Microstructure of welded AA6082 by TIG welding at (a) 100A and (b) 140A [44].

Effect of welding parameters of laser arc hybrid welding on weld quality of AA 6082, was studied and concluded that increasing arc current or laser power, or decreasing welding speed reduces weld percent porosity [45].

### Mechanical Properties of Welded AA6082

Non-fusion welding, specifically FSW for 6082-T6 exhibited a variation in mechanical properties of the joint with changing of process parameters [46]. Tensile strength of FSW welds was directly proportional to travel (welding) speed. Studying the variation of hardness through the weld zone, HAZ and TMAZ showed minimum values at the TMAZ of AA 6082. In the same time the fracture in tensile specimens coincided with the line of lowest hardness for AA 6082 [47].




| $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ |
|---|---|---|---|---|
| 1.4 | 31.7 | 2.0 | 818.1 | 28.4 |

**Figure 8.** Local true stress versus local hardness [48].

Linear stress-hardness relationship was established, relating the hardness in different AA 6082-T6 weld zones with local tensile properties. The welds were performed by friction stir welding (FSW) [48]. Relationship is shown in **Fig. 8**.

For Al-Mg-Si alloys the operating conditions for the T-joint continuous welding by continuous wave (CW) Nd:YAG laser for producing the maximum ultimate tensile load in the joints were investigated [49]. Filler wire feed rate and welding speed were the factors with strong influence on the tensile load of the assembly. Mechanical and metallurgical properties of extrusion welds of AA 6082-T4 showed less ductility in weld regions and precipitates of $Mg_2Si$ is the cause for premature failure at these locations [50].

Using TIG welding process to weld AA 6082 has an effect on mechanical properties of the welded joint. Shielding gas flow rate, welding current and filler material are among the main factors affecting tensile strength of the welded joint [51]. Thermo-mechanical analysis in TIG welding of AA 6082 proved its feasibility in measuring welding residual stresses [52]. Mechanical and metallurgical characteristics of dissimilar welded joints are the main problem to be solved using proper welding parameters. Welding AA 6082 with AA 5083 using pulsed current TIG welding showed better joint strength and hardness when using filler wire 5356 [53].

MIG welding process is spread in industrial applications. It is used successfully for similar welding of AA 6082 [54, 55] and dissimilar welding of AA5083 with AA 6082 [56]. Mechanical properties including tensile strength, Vickers hardness, Charpy impact strength and fatigue strength were measured for welded AA 6082 [55]. The residual strength of the welded joint recorded 60% of the parent metal. Reduction in tensile strength and hardness values were existed in HAZ. Fatigue test specimens, on the contrary fractured in WM where fracture toughness values calculated from Charpy V test (Eq. 1 [57]) exhibited its minimum values [55].

$$\left(\frac{K_{IC}}{\sigma_{YS}}\right)^2 = 0.64\left(\frac{CVN}{\sigma_{YS}} - 0.01\right) \qquad (1)$$

Especial interest had been forwarded to AA 6082-T6 when process modelling applied to this alloy weldments [58, 59]. Empirical formula (Eqs. 2, 3 [58, 59]) had been established to calculate yield strength and ultimate tensile strength using Vickers hardness test values (1 kg load).

$$R_{p0.2}(MPa) = 3.0\,HV - 48.1 \qquad (2)$$

$$R_m(MPa) = 2.6\,HV - 39.8 \qquad (3)$$

Toughness measured experimentally using CTOD test for welded AA 6082 showed better results compared to base metal while tensile results were poorer [60]. Postweld artificial aging for welded joints of AA 6082 markedly reduced the toughness. Full postweld heat treatment improved strength to base metal level, but toughness remained low [60].

Postweld heat treatment (PWHT) and shot peening effect on fatigue strength for MIG welded AA 6082 was discussed on the basis of variations in the microstructure (morphology and grain structure) of the weld metal [61]. After PWHT fatigue resistance increased with 26%, yield strength with 40% and ultimate tensile strength with 6% compared to as welded. Shot peening of the welded joints increased the fatigue resistance with 38% [61].

Fatigue behavior had been discussed for FSWed AA 6082-T6 [62, 63]. Due to compressive residual stress field at the crack vicinity, lower crack propagation rate was verified for the welded material in comparison with the HAZ or the base material [62]. Welding defects such as shear lips and tunnel _in particular_ formed in the retracting side of FSWed joint lead significantly to reduction of the fatigue lives of AA6082. Stress concentration created near shear lips have less effect on fatigue life than tunnel defect [63].

Standard test method followed in testing the base material of wrought or cast aluminum alloy products can be found at ASTM B557 – 84 [64]. To test welded joints, AWS B4.0 – 2007 is applied [65].

## CONCLUSIONS

The main concluding remarks those could be drawn from this revision are:

- Aluminum alloy 6082 is most widely used in the industrial applications including structures and aerospace.
- AA6082 can be welded successfully by fusion welding

using TIG or MIG welding processes, and non-fusion welding; namely FSW.

- Welding has negative effect on metallurgical and mechanical properties of the AA6082 welds either fusion or non-fusion welding processes.
- Postweld heat treatment enhances the microstructure to finer grains and hence the mechanical properties including tensile and hardness properties.
- Welding parameters in case of fusion welding those have considerable effects on mechanical characteristics include welding current, welding speed, filler wire material and filler feeding rate.
- In non-fusion welding FSW process, welding parameters affecting metallurgical and mechanical properties are rotational speed, travel speed and tool design.
- Fracture toughness of welded joints can be estimated using empirical equation made for AA6082. In the same way, yield and ultimate tensile strength can be calculated using empirical equation by measuring Vickers hardness values.
- After PWHT fatigue resistance of MIG welded AA6082 increased with 26%, yield strength with 40% and ultimate tensile strength with 6% compared to as welded. Shot peening of the welded joints increased the fatigue resistance with 38%.
- Lower crack propagation rate was verified for the welded material AA6082 in comparison with the HAZ or the base material due to compressive residual stress field at the crack vicinity.
- Welding defects such as shear lips and tunnel _in particular_ formed in the retracting side of FSWed joint lead significantly to reduction of the fatigue lives of AA6082.

## ACKNOWLEDGEMENT

The authors would like to thank Taif University for its financial support in the project No. 1/437/5241.

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