Dissimilar welding of aluminum alloys 2024 T3 and 7075 T6 by TIG process with double tungsten electrodes

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Abstract
The aim of this work is to study the metallurgical and mechanical properties of dissimilar assemblies of 2024 T3 and 7075 T6 structural hardening aluminum alloy by the TIG twine electrode arc welding process. It will include a weld performed according to optimized welding parameters followed by a study of the macroscopic and microscopic evolution of the dissimilar assembly (2024-7075) using optical and scanning electron microscopy (SEM); in addition, the phase compositions were analyzed with an energy dispersive spectrometer (EDS). Tensile and microhardness tests were performed. The tensile fracture was observed by SEM. This paper suggests that when the double tungsten electrode TIG welding is used, a stable arc has been formed with a good bead appearance. The heat dissipated by the arc generates several zones (molten zone (WZ), bonding zones (LZ), heat-affected zones (HAZ)) with different microstructures or precipitates of the type \( \theta (Al_2 Cu) \), \( S (Al_2 Cu, Mg) \) and \( \eta (MgZn_2) \), \( S (Al_2 Cu Mg) \) are formed in the heat-affected zone (HAZ) of base metals 2024 and 7075 respectively. The microhardness is lower in the molten zone and higher in the heat-affected zone of 7075 T6 alloy, which cried out an embrittlement and a 44% and 37% drop in the tensile strength of 7075 T6 and 2024 T3 base metals respectively.

Keywords 2024 and 7075 aluminum alloy · Aluminum with structural hardening · Microstructure · Double electrode TIG processing · Dissimilar welding

1 Introduction

Today, the search for new designs allows either to fulfill a new function or to lighten existing structures [1]. Aluminum and its alloys are some of the most widely used materials in the industry, especially in the aeronautics and aerospace industry.

The structural hardening alloys of the 7xxx and 2xxx series are the most widely used alloys; they are characterized by high mechanical strength and high corrosion resistance [2]. However, the assembly of these materials by welding is a challenge [3] for manufacturers and technologists, especially for heterogeneous assemblies. The difficulty stems from the high chemical reactivity of oxygen to aluminum, which produces a refractory layer of aluminum oxide and the high solubility of hydrogen, which generates porosities (blowholes). In addition, the high thermal conductivity generates lime cracks and deformations during welding, etc. [4–6]. For this reason, research has been carried out to study the feasibility of heterogeneous joining of aluminum alloys using TIG, MIG, high-energy LASER beam, and lately FSW.

Bai et al. [7] found that TIG and MIG arc sources are more advantageous than high-energy beams due to their efficiency and economy. Laser-arc hybrid welding processes are considered an efficient welding process; however, the deposition rate of the welding wire cannot be controlled independently of the welding current [8]. The FSW process allows several heterogeneous assemblies such as AA5754-AA7075 [9], AA2024-AA7075 [10], AA2219-AA5083 [11], and AA7075-AA6061

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However, Lakshminarayanan et al. [13] found that this process causes weakening at the bead (fusion zone) due to the dissolution or growth of reinforcing precipitates during the thermal welding cycle.

The TIG welding process is an abbreviation for tungsten inert gas. Although it is a stable arc process with high-quality weld beads, it suffers from low efficiency [14] where the deposition rate achieved is low compared to other welding processes. To overcome this shortcoming while retaining the benefits of TIG, a double electrode TIG welding technique has been developed [15].

Little research has been conducted on joining by “double electrode TIG.” It was initially launched by Yamada in 1998 [16, 17]. Then, it was further developed by Kobayashi et al., who used two tungsten electrodes in a torch salt to improve the welding efficiency of thick plates of PCLNG (9% Ni-based steel) storage backs and obtained a higher deposit without sacrificing the advantages of the conventional TIG process [14]. Subsequently, comparative studies conducted by Wand Bao [18] on low carbon steel sheets with a thickness of 3 and 4 mm revealed that welding by this process is significantly better than welding by the conventional process since it reduces welding defects such as metal collapse, pitting, etc. Research is still ongoing, but in the theoretical view, there are simulations of the thermal phenomena of plasma arc welding.

In 2012, Zhang et al. [15] determined the dependence of temperature distribution of the coupling arc on the arc current, arc length, and the distance between the two electrodes. He found that the maximum temperature in the high-temperature region is located in the middle of the two electrodes while the maximum temperature of a single arc is located under the electrode. In 2014, Wang et al. [19] designed a numerical model that links the effect of plasma arc on the melt in the presence of oxygen in order to investigate the arc coupling behavior. The scope of the investigation included the distributions of temperature, velocity, pressure and current density, and the pattern of heat transfer and liquid flow in the melt exerted by the arc coupling. He found that the distributions of arc pressure, current density, and heat flux at the anode are not rotationally symmetric, and cannot be described by Gaussian approximations. Another model was developed by Ding et al. [20] to describe the arc characteristics of welding generated by the tungsten inert gas process with the double electrode. He found that the simulated results indicate higher values of arc temperature obtained by helium gas compared to argon gas. Subsequently, in 2016, Schwedersky [21] presented two-dimensional measurements of pressure generated by the tungsten inert gas process with the double electrode (T-TIG); he found that arc pressure values were much smaller for TIG with double electrode compared to those of TIG with a single electrode in the same total current. Moreover, he observed an electromagnetic interaction between the arcs, which varied according to the distance between the electrodes.

As revealed by the literature review, the studies on this technique have dealt with the welding of high-alloyed steels based on nickel (9 Ni) and steels with low carbon content, but have not taken into account metallurgical and mechanical aspects. For this reason, the aim of our work is to use this technique (TIG welding with double tungsten electrodes) for a metallurgical and mechanical study of a dissimilar weld of two aluminum alloys with structural hardening 2024–7075.

## 2 Materials and methods

The experimental equipment includes two Miller Dynasty 350 TIG (AC/DC) current generators, three bottles of extra pure argon gas (99.9999%) to ensure the protection of the up and down the molten bath, a cart to ensure the speed of the welding movement, and a camera to capture the arc at the time of welding (Fig. 1).

For our system, to be a double electrode TIG process, the torches of the two generators are fixed in a jig on the carriage so that the electrodes are separated from each other and the height between the workpieces and the electrodes is ~ 4 mm.

The raw material of our base metals were sheets of aircraft-grade aluminum alloys obtained from a local air carrier (Air-Algerie) of the type 2024 treated in the state T3 and type 7075 treated in the state T6 with a thickness of 2.5 mm. The assembly of the plates was carried out by filler wire of an aluminum alloy type ER: 5356 with 2 mm of diameter. The chemical and microstructural analyses of the latter were performed by a spark gap spectrometer and by metallography as shown in Table 1 and Fig. 2.

Before welding, the sheets were cut into 200 × 100-mm pieces, then cleaned by a stainless steel wire brush to crush the oxide layer (Al2O3), and pickled by acetone to remove grease. Next, they were pointed butt to butt and fixed by a clamping system.

After welding, samples were cut, including transversal sections, and polished with a series of abrasive papers from 220 to 4000; then, the final polishing was done by a felt paper with a diamond suspension of the grain of 3 and 1 μm. The sample was etched with a KELLER chemical solution (1 ml HF 48%, 1.5 ml HCl, 2.5 ml HNO3, 90 ml H2O) for metallographic and SEM observations. The observations were made by a Nikon optical microscope (×1500 magnification), and a scanning electron microscope (SEM) brand ZEISS Gemini SEM 300 equipped with an energy dispersive spectrometer (EDS). To assess the quality of the mechanical properties of our welds, two tests were performed: the first was a microhardness test and the second was a tensile test. Microhardness measurements were determined with an automatic Vickers microhardness tester (BUEHLER WILSON VH3300). The tensile test
was performed on a universal machine type MTS Criterion model 45, 100 KN; the test was applied to a specimen sized in Fig. 3.

3 Results and discussions

To ensure the right choice of welding parameters and to achieve a good arc stability, several studies were conducted on the current intensity, the voltage, and the shielding gas flow; Table 2 presents our choices of the welding parameters with a double electrode TIG.

Fig. 4 shows the welding arc used. It can see that the arc is stable with a Gaussian distribution, much lower than that of the arc of simple TIG as was exhaustively documented by Ogino [22] in his article. Fig. 5 illustrates the weld bead appearance of the two sheets welded on both up- and downsides.

The visual inspection of the bead shows a neat aspect on both the up and downsides without any defects (cracks, channels, etc.) all along the welding joints, which can be explained by the good superposition of the solidification stripes on each other. The average width is about 8 mm on the upside and 6 mm on the downside. The mechanical strength of the welds is often related to the structural morphology and the presence of secondary phase particles in the matrix. The chemical nature, quantity, and location of these particles will be important parameters for understanding the phenomena related to the lowering of mechanical properties that generate sharp rupture [23].

3.1 Microhardness

Fig. 6 shows the evolution of the microhardness profiles measured across the welded joint from left to right, including the base metals (BM 2024 to BM 7075), the heat-affected zones (HAZ 2024, HAZ 7075), the liaison zones (ZL 2024, ZL 7075), and the fusion zone (WZ), as shown in Fig. 6. Vickers indenter is applied on the cross section under a load of 300 g with a pitch of 300 μm.

It can be seen that the microhardness is more basic in the molten zone with an average value of 96 HV, followed by an increase of about 109 HV and 125 HV in the bonding zones.
ZL2024 and ZL7075 successively, then a rapid increase up to

Fig. 2 Microstructures of base metals

![Microstructures of base metals](image)

(a) 2024 T3  
(b) 7075 T6

Fig. 3 Tensile test piece

![Tensile test piece](image)

Fig. 4 Double electrode arc

![Double electrode arc](image)

Fig. 5 Welding bead aspects

![Welding bead aspects](image)

Table 2  Welding parameters

| Welding process | N° Welding pass | Wire diameter (mm) | Welding current I (A) | Welding voltage U (V) | Welding speed v (mm/s) | Flow rate Q (l/min) | Welding energy E (J/mm) |
|-----------------|-----------------|--------------------|-----------------------|-----------------------|------------------------|---------------------|------------------------|
| TIG             | 1st pass (up)   | 2                  | 60-60                 | 9.5-9.5               | 3                      | 15                  | 266                    |
| TIG             | 2nd pass (down) | 2                  | 60-60                 | 9.5-9.5               | 3                      | 15                  | 266                    |
Fig. 6 Microhardness profiles across the weldment

Fig. 7 Optical macrograph of the different areas of the welded joint
a maximum value of 148 HV and 185 HV, and the heat-affected zones of HAZ 2024 and HAZ 7075 respectively. This increase is followed by a drop in microhardness in both metals to approximately 107 for HAZ 2024 HV and 110 HAZ 7075 and, finally, a return increase with an average microhardness value of 120 HV and 152 in the base metal BM2024 and BM 7075 respectively

3.2 Macrostructures and microstructures analysis

The metallographic observations were made on the plane perpendicular to the rolling direction. Fig. 7 presents the macrography of the weld bead, where we can distinguish several zones such as the molten zone (WF), liaison zone (ZL), thermally affected zone (HAZ), and finally the base metal (BM).

These changes in microstructure related to temperature gradients have been addressed in many different works [24]. However, the literature is poor in studies of heterogeneous weld joints of aluminum alloys as is the case of double electrode TIG welding processes.

As shown in Figure 7, the melted zone (WZ) is about 8 mm, the bond zones are 0.6 mm, and finally, the coarse-grained heat-affected zones (HAZ) are about 4 mm.

Fig. 2 above shows the metallographic structure of the base metals. It can be seen that the structure of both metals is

![SEM micrograph and EDS chemical analysis of base metals](image)

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(a) 2024

(b) 7075
elongated grains, which can be attributed to the lamination effect, with dark coarse precipitates.

Lin et al. [25] found that the precipitation hardening of 2024-T3 aluminum alloys during creep aging. The main coarse particles are impurity phases or equilibrium phases. In general, the insoluble particles are the coarsest with irregular forms and complex compounds of the chemical elements Fe, Cu, Si, and Al which is well shown in Figure 8, where the irregular particles are rich in iron and copper, proving the presence of the Al₂Cu₂Fe phase. On the other hand, Cochard [26] and Kaker [27] found that the equilibrium phases are microparticles of round shapes. For this reason, the round-shaped particles in Fig. 8a and Fig. 8b are precipitates of type (Al₂Cu), S (Al₂Cu Mg) and (Mg Zn₂), S (Al₂Cu Mg) respectively.

Fig. 9 shows the central zone of the weld (molten zone WZ). This zone is obtained from a liquid/solid transformation, with a rather slow solidification [28]. A marked segregation is also apparent in this zone. In terms of grain structure, it is characterized by a dendritic equiaxed structure [26] with an aluminum solid solution (α-Al) contoured by grain boundaries.

Lefebre [28] and Rhodes [29] noted that in the melting zone, the interdendritic particles were identified as Cu and Zn rich phases, but with a significantly low proportion of Mg to form the ternary phase S (Al₂CuMg). They were found to be eutectics of type α – Al + θ(Al₂Cu) and Al Zn-Mg, as we presented in the figure of chemical element mappings (Fig. 9) of the molten zone (WZ).

At the end of the molten zone, partially molten bonding zones are formed as shown in Fig. 10; they are heated above the solidus and eutectic temperature. They are characterized by elongated columnar grains with some epitaxy developing in the opposite direction to the heat removal [30].

It was found that liquefactions are formed at the boundaries of the grain boundaries, which contain intermetallic phases of the type Al₂Cu [31], Al₂CuMg plus eutectic Al-Cu-Mg [32, 33] in the 2024 side and MgZn₂, Mg (Al, Zn)₂ plus eutectic Al-Zn-Mg [29] on the 7075 side, which is shown in the figure of the EDS chemical analysis maps (Figure 10). When our alloys are heated rapidly above the solvus temperature, the intermetallics and residual eutectic do not have enough time to dissolve completely in the matrix because solid-state diffusion is slow. Therefore, when heated to the eutectic temperature, the residual intermetallic phase reacts with the matrix and forms the liquid eutectic at the interface [30, 31].

Just next to the partially melted zones, heat-affected zones are presented in Fig. 11. During solidification, the temperature is below solidus; therefore, it is too low for the formation of a melt, but sufficient to provoke important microstructural modifications.

These areas are undergoing solid/solid transformations, and precipitation and grain growth are observed [31].

As shown in the MAB micrographs and the EDS chemical analysis maps, it was found that there is a magnification in the vicinity of the partially melted zones on both sides (2024 and 7075). Norman [34] and Elrefaey [35] have well explained the sequence of precipitates in the structural aluminum alloys t alc 2024 and 7075 and confirmed by transmission electron microscopy (TEM) that in the vicinity of the solvus temperature an absence of the Al-Cu-Mg and Al-Zn-Mg phases, which causes a natural aging to occur thereafter, restoring the properties of the base alloy.

At some distance from the partially melted zones (center of the HAZ), the temperature is below the solvent temperature and above 200 °C; the predominant phases are S in alloy 2024 [34] and η in alloy 7075 [35]. This will induce overaging,
where any precipitate will be coarse and will inevitably produce an aged microstructure.

Finally, the HAZ areas are adjacent to the base metals where the temperature is below 200 °C; the base materials (2024 and 7075) recover an artificial aging treatment and will produce precipitations of the reinforcing phase $S'$ and $\eta'$ ($\text{MgZn}_2$) of the base metals respectively [36].

3.2.1 Microstructure—microhardness: discussion

From Figure 6, the variation of the microhardness is caused by the structural changes during welding. The microhardness is lower in the melting zone (WZ), where most precipitates dissolve [31]; then, the microhardness increases a little in the partially melted zone, where the grains are elongated with liquefied joints and contain some precipitates of type (Al$\text{Cu}$) and S (Al$\text{Cu}$ Mg) [34] in LZ 2024 and of type $\eta$ (Mg $\text{Zn}_2$) and Mg (Al, $\text{Zn}_2$) [31, 33]. After that, it continues to rise to its maximum in the thermally affected zone; in this zone, the temperature is close to the vicinity of the solvus, which causes subsequent natural aging to occur later, restoring the properties of the base alloy. A little far from the partially molten zones (center of the HAZ), the microhardness decrease or the temperature is between $T_v$ (solvus) and 200 °C; the S and $\eta$ phases are coarse and more important in 2024 alloy [32] and 7075 alloy [33] respectively. This will induce overaging. Finally, in the HAZ areas adjacent to the base metals, the microhardness increases where the temperature is below 200 °C; the base materials (2024 and 7075) recover an artificial aging treatment and will produce precipitations of the reinforcing phase $S'$ and $\eta'$ ($\text{MgZn}_2$) of the base metals respectively [36].
°C; the base metals 2024 and 7075 recover an artificial aging treatment and will produce precipitations of the reinforcing phase \( S' \) (Al2CuMg) and \( \eta' \) (MgZn2) of the base metals respectively [34, 36].

### 3.3 Traction

In general, the tensile test is a destructive test used for the purpose of characterizing the mechanical behavior and evaluating the mechanical properties of traction such as yield strength, maximum tensile strength, and elongation [37]. For this purpose, the test was carried out on a universal machine, with a tensile speed of 0.05 mm/s; the specimens were taken perpendicular to the direction of welding.

Fig. 12 shows the micrograph of the fracture surfaces of the dissimilar assembly tensile specimen (2024-7075) while the results of the tensile test are presented in Table 3.

As shown in the table, the maximum tensile strengths of 7075T6 and 2024 T3 base metals are 515.89 and 459.67 MPa, respectively. Thus, the elongation and maximum tensile strength of the welded joint are 2.62% and 288.35 MPa, respectively. This shows a 44% and 37% reduction in the strength of the welded joint unlike those of the base metals 7075 and 2024, respectively. However, the results obtained from this work are satisfactory because they are consistent with works involving friction stir welding technique such as those done by Saravanan et al. [38], Padmanaban [39], and Avinash [40].
It can be seen that the weld is fractured at the heat-affected zone on the 7075 T6 alloy side (Figure 12 b and c).

SEM micrographs of the fracture surfaces (Figure 12 d and e) show that the fracture surface is inter-granular. As shown in the microstructures and microhardness profiles, this area contains brittle precipitates with a significant microhardness. In addition, the faces seem to be brittle failures since the surfaces are flat and show almost no signs of plastic deformation [41].

4 Conclusion

In this work, sheets of dissimilar aluminum alloys (2024 and 7075) were welded by the TIG arc welding process with double tungsten electrodes, and the microstructural and mechanical properties of the joint are studied. The main findings are summarized as follows:

1. The stable arc with double tungsten electrodes preceding TIG will produce good weld bead aspects explained by the good superposition of solidification striations and the lack of microscopic defects such as porosities. This has a positive effect on the quality of the weld.
2. The energy dissipated by the heat source creates several zones (molten zone, heat-affected zones), which can be explained by structural changes.
3. The heat-affected zones are reduced compared to the conventional TIG welding process. Precipitates of the type Al2Cu (θ phase) and Al2Cu Mg (S phase) and η (MgZn2) are formed in the heat-affected zone.
4. The hardness is lower in the molten zone because the hardening precipitates are dissolved during melting and no structural hardening reaction takes place at this temperature.
5. The maximum load of the assembly 2024 T3-7075 T6 shows a reduction of 44% and 37% to those of the base metals 7075 T3 and 2024 T3.

| Table 3 Mechanical properties of tensile tests |
|-----------------------------------------------|
| Material               | Ultimate tensile strength (MPa) | Yield strength 0.2% (MPa) | Elongation (%) |
|------------------------|-------------------------------|---------------------------|----------------|
| Base metals 2024 T3    | 459.67                        | 288.56                    | 12.23          |
| Base metals 7075 T6    | 515.89                        | 460.054                   | 7.54           |
| Welding metals 2024 T3-7075 T6 | 288.35                    | 120.72                    | 2.62           |
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