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Formation of weld defects in cold metal transfer arc welded 7075-T6 plates and its effect on joint performance

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Abstract. This study aims at investigating the formation of weld defects (i.e., pores) and determining the effect of pores on mechanical performance of the AA7075-T6 plate joints produced using cold metal transfer (CMT) gas metal arc welding (GMAW) technique. For this purpose, AA7075-T6 Al-alloy plates with a thickness of 2 mm were joined using CMT welding technique. The microstructural and mechanical properties of the welded plates were investigated by detailed optical microscopy investigations, micro-hardness measurements and tensile tests. A correlation between the joint performance and the formation of porosity in the fusion zone (FZ) was also attempted to show the effect of the presence of large pores on the mechanical behavior of the joint.

1. Introduction

Al-alloys, are widely used in transportation industry particularly in applications where lightweight is required owing to their excellent specific strength and fracture properties, high-formability, good corrosion resistance [1]. Among Al-alloys, age hardened AA7075 alloy (i.e., T6) has a superior strength which is comparable with that of steel [2]. The weldability is one of the main challenges for the use of a material in commercial application. Conventional fusion welding of Al-alloys, especially in age hardened condition, have several difficulties such as porosity formation, solidification cracking and significant strength loss in the joint [2-7]. The main reason for these problems is the high heat input occurred during these welding processes. One way of avoiding these problems is to use solid state welding techniques such as friction stir welding (FSW), which are inherently low heat input joining techniques. Thus, numerous studies have been conducted over the last three decades on FSW of Al-alloys [2,3,8-19] as well as other structural materials, such as pure Pb [20], Cu-alloys [21], Mg-alloys [22], and higher melting temperature materials (i.e., steels) [23,24]. Another approach to avoid weld defects and to produce sound joints in age hardened Al-alloys is to use lower heat input fusion welding processes. For instance, Cold Metal Transfer (CMT) welding process, which is based on the Gas Metal Arc Welding (GMAW) – also known as MIG, developed by Fronius of Austria in 2004, has an advantage for welding of Al-alloys [25,26]. CMT technology has different variants, such as conventional CMT, CMT pulse (CMT-P), CMT advanced (CMT-ADV) and CMT pulse advanced (CMT-PADV) and experiments were performed on both single layer deposits and multilayer deposits [27].

There are very limited reports on CMT welding of AA7075 alloy [28]. Thus, there is certainly a need for further research on CMT welding of this alloy, which was the motivation for this research. In this study, AA7075-T6 Al-alloy plates with a thickness of 2 mm have been welded using CMT welding technique. Detailed optical microscopy investigations, microhardness measurements and tensile tests

have been conducted to investigate the microstructural and mechanical properties of the welded plates and to correlate the joint performance with microstructural aspects, such as the formation of porosity in the fusion zone (FZ).

2. Experimental procedure

AA75075-T6 plates with a thickness of 2 mm were used in this study. In order to conduct the robotic CMT welding technique, specimens with dimensions of 15 x 25 x 2 mm were extracted from as received base plate. The weld surfaces to be welded were only mechanically cleaned using metal brush prior to the joining process. No further cleaning was conducted. ER5356 with a diameter of 1.2 mm was sued as filler wire. The weld parameters used during welding are listed in the table 1. Argon shielding gas was switched on 0.1 s before and was switched off 0.5 s after the arc was struck.

Table 1. The weld parameters used during welding.

Material	Current (A)	Voltage (V)	Weld speed (mm/min)	Wire feed rate (mm/min)	Shielding gas rate (l/min)
AA7075-T6	120	15.2	900	1100	15

A metallography specimen and four tensile test specimens were extracted from each joint produced in order to evaluate microstructural and hardness variations within the weld region and to determine tensile properties, i.e. weld performance values. Metallography specimens were ground and polished and then etched for 120 s using Keller's reagent for microstructural investigations and microhardness measurements. A detailed optical microscopy was conducted along the cross-sections of the joints produced in order to evaluate the microstructural alterations taking place within the weld region (i.e., FZ and heat affected zone - HAZ) and the formation of porosity in the FZ. Vickers micro-hardness measurements ($HV_{0.2}$) were conducted across the weld cross-section on a line in the mid-thickness of the welded joint at numerous locations using a load of 200 g in order to determine the hardness profile of the joint produced. The tensile tests were conducted on the standard transverse tensile specimens extracted from the as-received base plate and the welded joint using a loading rate of 0.1 mm/min. Furthermore, a detailed optical microscopy was also conducted on the specimens after the tensile test in order to correlate the microstructural aspects to the mechanical properties of the joints and to determine the fracture mode of the joint under tensile loading.

3. Results and discussion

3.1. Microstructural aspects

A macrograph taken from the welded joint produced in this study is given in figure 1. As seen from this figure, the welded joint did not exhibit any cracks. On the other hand, there is relatively extensive porosity formation in the FZ. This is in contrast to the results reported by Elrefaey [28] who observed very small amount of relatively small pores within the FZ of the CMT welded 7075-T6 joints produced using very similar weld parameters. However, they employed cleaning of the surfaces with acetone prior to welding whereas only mechanically cleaning using metal brush was used in the current study. Thus, the reason of the porosity formation in the FZ of the joint is attributed to the insufficient cleaning procedure applied prior to the joining process to remove the oxide layer and other contaminants in the current study. Another reason for extensive pore formation might be the high cooling rates involved after the welding in the current study.

The microstructure of AA7075-T6 base plates used in this study are shown in figure 2(a). As seen from these micrographs, base plate exhibits a microstructure consisting of alpha grains containing undesirable inhomogeneously distributed iron- and silicon-rich particles in the form of coarse constituent particles which are readily visible in optical microscopy. As reported in earlier publications [13,16,17], the particles randomly oriented in alpha matrix are Al_7Cu_2Fe, $Al_{12}Fe_3Si$, and Mg_2Si particles. The microstructure of AA7075 alloy also contains very fine grained $MgZn_2$ precipitates

homogeneously distributed within the alpha grains, which result in strengthening in T6 temper condition of this alloy. However, these strengthening precipitates ($MgZn_2$) are extremely fine, so that they are not visible under optical microscope, and even in scanning electron microscopy.
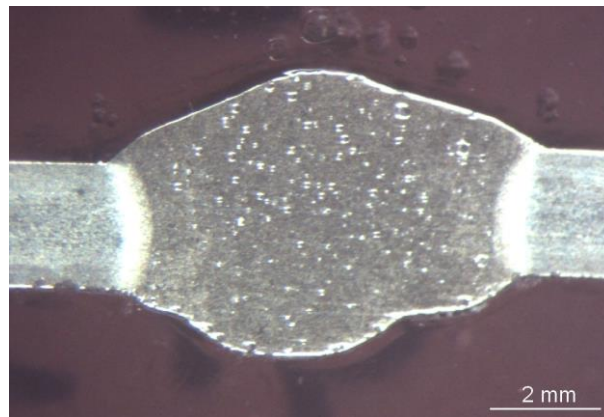

Figure 1. Macrograph taken from the CMT Welded joint.
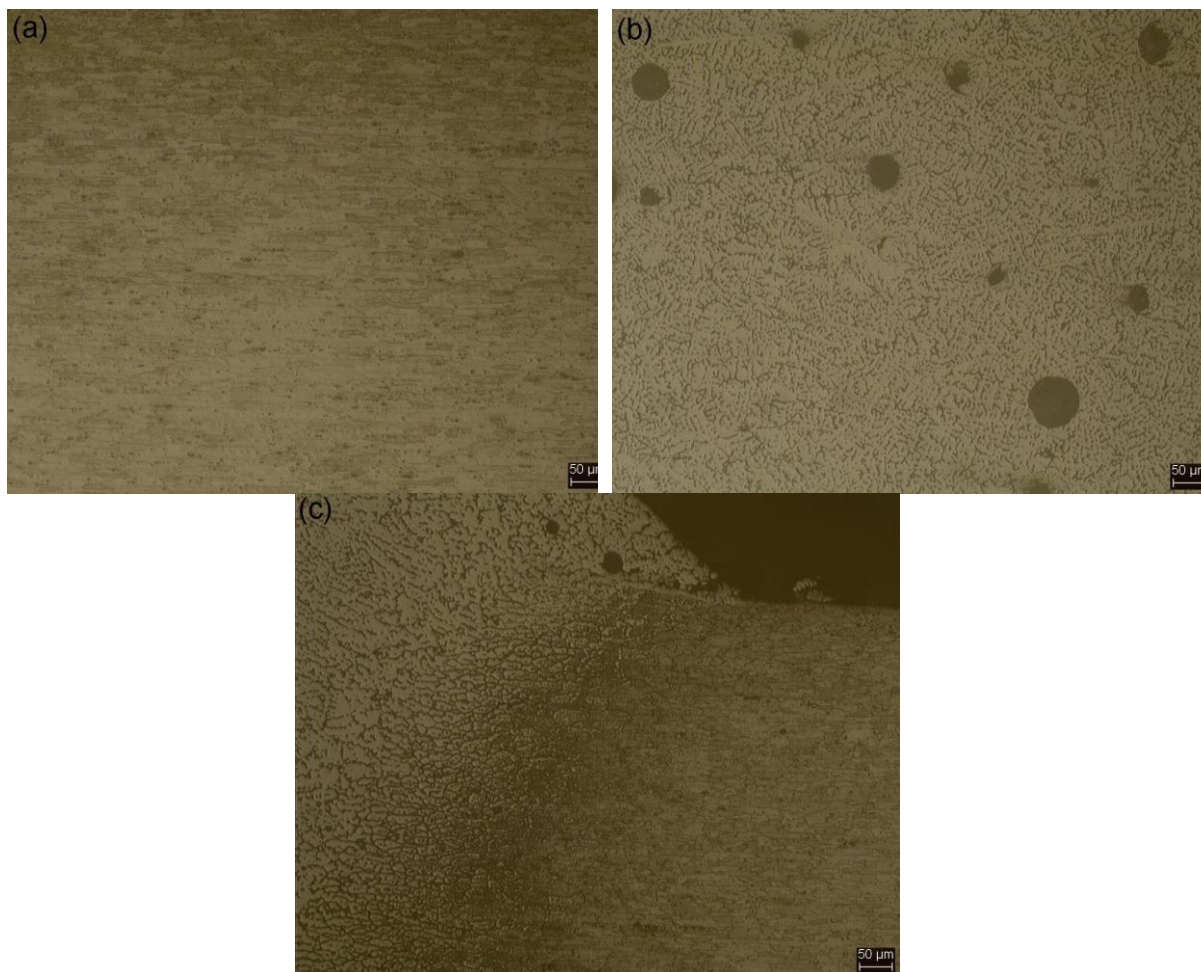

Figure 2. Optical micrographs of 2 mm thick base plate and different weld zones of the joint produced on this plate: (a) base plate, (b) weld zone, (c) transaction zones.

As clearly seen from figure 2(b), FZ exhibited a dendritic structure with some particles due to the

solidification of the fusion zone taking place after the welding. Furthermore, significant amount of large pores were clearly observed in the FZ as mentioned earlier. On the other hand, a refinement of alpha grains and coarsening/dissolution of strengthening particles took place in the HAZ regions as shown in figure 2(c).

3.2. Mechanical properties

Figure 3 illustrates the hardness profile of the joint produced. As clearly seen from figure, the hardness loss took place in the weld region, the minimum hardness, i.e., about 65 HV, lying in the FZ. This is not surprising since a hardness loss usually takes place in the weld region of fusion welded age-hardened Al-alloys [4-7]. The reason of the hardness loss in the FZ and HAZ is the evolution of dendritic structure and the coarsening of strengthening precipitates due to overaging, respectively. The base plate used in this study is in the artificially aged temper condition (i.e., T6) and the strength in this temper condition originates mainly from very fine homogeneously distributed strengthening precipitates within the alpha grains. When this alloy is exposed to heat after aging, such as welding, dissolution of precipitates and evolution of a dendritic structure and coarsening of the strengthening precipitates takes place in FZ and HAZ regions, respectively as mentioned above, thus resulting in a loss in hardness in both regions. Similar results were also reported by Elrefaey [28] for CMT arc welded AA7075-T6 plates. The hardness level observed in the FZ in current study is slightly lower than that reported by [28].

The hardness profile of this fusion welded joint is somewhat different than those usually observed in fusion welded or friction stir welded AA7075-T6 joints in which the hardness minimum lies within the overaged HAZ regions on both sides of the weld nugget since hardness loss in the weld nugget is partly recovered by the grain refinement taking place there, giving rise to a W-shaped hardness profile [16]. Although there is a hardness loss in the overaged HAZ regions on both sides of the FZ of this joint as well the hardness loss is not as significant as those in the HAZ regions of conventional fusion welded or friction stir welded AA7075-T6 joints [16]. On the other hand, the hardness profile obtained is very similar to those reported for lower heat input fusion welded (i.e., electron beam or laser beam welded) age-hardened Al-alloys [4-7].
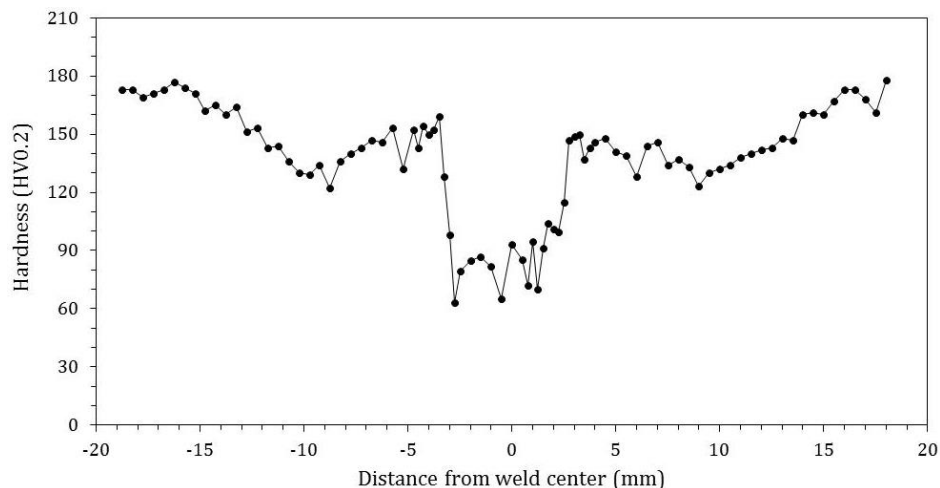

Figure 3. Hardness profile of the joint produced.

The tensile test results are summarized in table 2. Three tensile tests were conducted for the base plate and the joint and the average of these three test results were calculated, and the average values calculated are given in table in bold and parenthesis. These average values were used in the calculations of the joint performance value in terms of tensile strength. The tensile strength performance value was determined as explained below:

Tensile strength performance (%) = (Tensile strength of welded joint / tensile strength of base plate) x 100

Table 2. Tensile test results.

Specimen	0.2% Proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Tensile strength performance (%)
Base Metal	526; 550; 541 (**539**)	589; 605; 597 (**597**)	14.2; 14.7; 14.9 (**14,6**)	---
Welded Joint	---	304; 307; 315; 323 (**312**)	0.002; 0.004; 0.005; 0.002 (**0.003**)	52

As seen from table 2, the tensile strength performance value was found to be about 52%. This value was somewhat lower than that reported by [28], i.e, 60%. These results are in agreement with the fact that there is a significantly higher amount of pores in the FZ of the joint produced in this study those reported by [28]. Moreover, the pores present are much larger in size than those reported by [28]. The reason of the formation of more and larger pores in the current study is apparently the inadequate surface cleaning prior to welding as discussed earlier in microstructural aspects section. This result is also in good agreement with the hardness profile of the joint, figure 3. As seen from figure 3, the hardness minimum in the FZ of the joint and the hardness loss in this region is significant, i.e., about 110 HV (the hardness value being about 65 HV in the FZ compared to about 175 HV in the base plate). Moreover, the elongation value exhibited by the joint is extremely low, being 0.03%. This is partly due to the strength undermatching in the FZ. Since the strength is much lower within the FZ than that of the base plate the elongation takes place only within the weld region section of the transverse tensile test specimens and the base plate sections do not yield (it is in the elastic region throughout the test) and thus do not contribute to the total elongation. In the case of strength undermatching joints, the stress concentration and, thus, the fracture take place in the lower strength weld metal region (confined plasticity), leading to an increase of constraint within the weld region and, thus, significantly lower ductility levels. This confined plasticity is also quite common in fusion welded or diffusion bonded joints with a strength undermatching weld region [2-7,29-32]. Moreover, another reason of this extremely low elongation is the presence of large pores within the FZ, as seen in figure 2(b). As He *et al* [33] pointed out as well, the local deformation in the FZ was concentrated around the porosities in the case of the existence of pores. Thus, this accelerates the failure of the specimen and reduces the global ductility remarkably.

The detailed metallographic study conducted on the fractured transverse tensile specimen of the joint clearly indicated that the failure took place within the FZ next to the transition region between FZ and HAZ regions. This is not surprising due to the strength undermatching of the joint. On the other hand, this detailed fractography clearly revealed that the presence of large pores influenced the failure mode by dictating the crack growth path. As clearly seen from figure 4, the failure of the specimen took place along the transition region between the FZ and HAZ within the FZ by the jumping of the crack from pore to pore, i.e., bridging of pores. Thus, this led to a kind of brittle failure, consequently to an extremely low elongation, although the FZ is very low strength (i.e., soft) indeed.
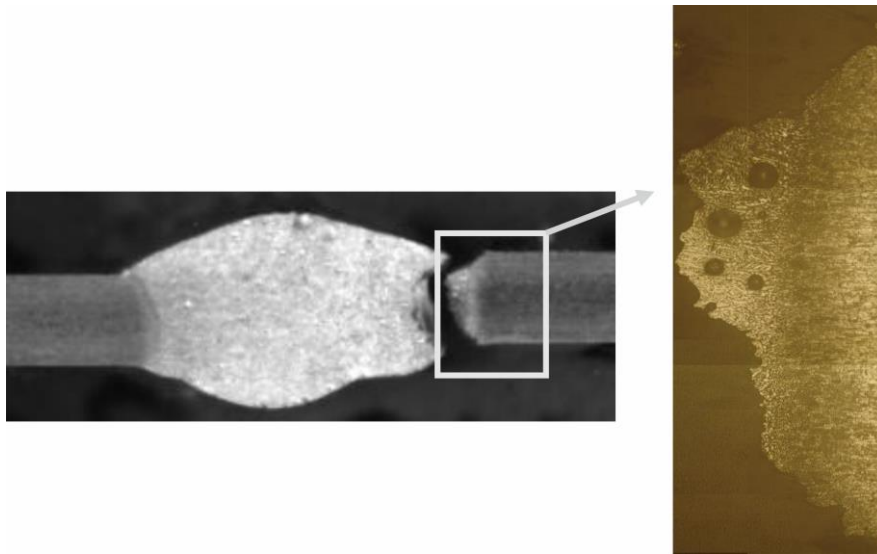
Figure 4. Macrograph of the transverse tensile test specimen showing the fracture location and higher magnification micrograph taken from the fracture area marked with a rectangular illustrating the fracture path. Note the crack propagation within the FZ next to the HAZ and the crack growth taking place by bridging from one pore to another.

4. Conclusions

In this study, AA7075-T6 Al-alloy plates with a thickness of 2 mm, have been welded using CMT arc welding technique. The following conclusions have been withdrawn from this experimental work:

- A dendritic structure containing a significantly high volume percent of large pores was observed in the FZ. The reason for the formation large pores is the inadequate surface cleaning prior to welding.
- The hardness minimum was exhibited by the FZ where a dendritic structure is present. A hardness loss was also observed in the HAZ regions on both sides of the FZ. However, the hardness decreases in these regions are much less significant than that taking place in the FZ. This can be attributed to the lower heat inputs involved during CMT welding leading to a finer grained structure and reduced coarsening of strengthening particles in the HAZ regions.
- The tensile strength performance of the joint was found to be about 52%, which is in good agreement with the hardness profile obtained from the joint, in which the hardness minimum lies in the FZ.
- The elongation value exhibited by the joint was extremely low. This is not surprising since lower ductility levels are usually obtained from the transverse tensile specimens extracted from the joints with strength undermatching weld zone due to confined plasticity. Another reason for this low ductility is the presence of large pores in the FZ, which results in concentrated local deformation within the FZ and thus accelerates the failure of the specimen and reduces the global ductility remarkably.
- The presence of large pores also influenced the failure mode by dictating the crack growth path. The crack propagated by jumping from one pore to other within the FZ, thus rendering brittle failure.

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