Effect of zirconium addition on welding of aluminum grain refined by titanium plus boron

A I O Zaid
Industrial Engineering Department, University of Jordan, Amman, Jordan
E-mail: a_kilani43@hotmail.com

Abstract. Aluminum oxidizes freely in ordinary atmosphere which makes its welding difficult and weak, particularly it solidifies in columnar structure with large grains. Therefore, it is anticipated that the effect of addition of some grain refiners to its melt before solidification is worth while investigating as it may enhance its weldability and improve its mechanical strength. In this paper, the effect of addition of zirconium at a weight of 0.1% (which corresponds to the peritectic limit on the aluminum-zirconium base phase diagram) to commercially pure aluminum, grain refined by Ti+B on its weldability, using gas tungsten arc welding, GTAW, method which was formerly known as TIG. A constant current level of 30 AC Ampere was used because it removes the oxides during the welding process. Metallographic examination of the weldments of the different combinations of Al with Al and Al with its microalloys: in the heat affected zone, HAZ, and away from it was carried out and examined for HAZ width, porosity, cracks and microhardness. It was found that grain refining by Ti+B or Zr resulted in enhancement of the weldment.

1. Introduction
Aluminum and its alloys are versatile and very attractive materials due to their high strength–to-weight ratio, high electrical and thermal conductivities with respect to their weight good corrosion resistance and appearance. Due to these properties Al and its alloys are widely used in engineering and industrial applications particularly in the automobile and air craft industries. Beside these useful properties they have the disadvantage of solidifying in columnar structure with large grain size which tends to deteriorate their mechanical strengths and surface quality [1]. Therefore it became a necessity to grain refine their structure with some grain refiners e.g. Ti, Ti+B, V, Mo etc. to the melt prior to solidification [1,2,3].

Welding is one of the most important means of fabrication and maintenance processes in industry. It is used in joining different alloys in different shapes and applications. The gas tungsten arc welding method, GTAW, which is formerly known as TIG is very often used for welding aluminum, magnesium, titanium and their alloys particularly in welding aluminum and its alloys. It is generally preferred because it produces very high quality welds. Furthermore, the control of distortion which is a major problem in welding of thin sections [4]. To achieve good and strong welds and avoid defects, considerations should be given to the selection of the welding process and the parameters affecting it. In general, the strength and the quality of the weldment are strongly affected by the process parameters which in TIG welding includes: welding current, polarity (DCSP/DCRP), arc voltage (arc length), travel speed, weld joint position, electrode diameter and shielding gas composition and flow rate. The results of the research on the effect of these parameters indicated that they have profound
effect on the strength and quality of the weld. Knowledge and control of these variables is essential to consistently produce sound welds of good quality and strength. It is worth mentioning that these variables are not completely independent and changing one requires changing one or more of the others to achieve the desired results, [5,6,7,8,9].

Weld fusion zones typically exhibit coarse columnar structure due to the prevailing high temperature of the weld metal solidification, specially in the case of aluminum and its alloys. This normally results in inferior weld mechanical properties and poor resistance to hot cracking. Hence, it is highly desirable to control solidification structures in welds specially in the HAZ region, which is often very difficult to do so, because of the higher temperatures and the high thermal gradients in the fusion zone. This is unlike the case in casting process of these alloys. Different attempts have been tried for refining the structure in the weld fusion zone, e.g. inoculation with heterogeneous inoculants, microcooler, additions, surface nucleation induced by gas impingement and introduction of physical disturbance techniques such as torch vibrations [10,11,12]. It is worth noting that the use of inoculants for refining the weld fusion zones involves undesirable effects of inoculating elements which tends to adversely affect the mechanical properties of the weld in the HAZ (weld fusion zone), when the inoculants are added to the level which will cause grain refinement. Similarly, the surface nucleation and microcooler additions were also turned down because of the complicated welding setups required and procedures associated with their use. Recently, two techniques namely, magnetic arc oscillation and the current pulsing have gained popularity due to their promising results and the relative ease by which these techniques can be applied to practical and industrial application with only minor modifications to the existing welding setups. The advantages of the pulsed and magnetic arc oscillation welds is claimed to include grain refinement in the fusion zone with reduced width of HAZ which leads to less distortion, control of segregation, reduced cracking sensitivity and reduced residual stresses [13]. Optimization of the pulsed TIG welding process parameters using Taguchi method aiming for increasing the mechanical properties of the weld was investigated and reported [9]. To the best of the author's knowledge the effect of addition of grain refiners on the weldability of Al has not been previously investigated. In this paper, the effect of addition of zirconium to aluminum grain refined by Ti+B on its weldability is investigated.

2. Materials, equipment and experimental procedures

2.1. Materials

2.1.1. Base metal
Commercially pure aluminum 99.8% purity of the chemical composition shown in table 1 was used throughout this work.

| Element | Fe | Si | Cu | Mg | Ti | V | Zn | Mn | Na | Al |
|---------|----|----|----|----|----|---|----|----|----|----|
| Wt. %   | 0.09| 0.05| 0.005| 0.004| 0.004| 0.008| 0.005| 0.001| 0.005| Rem. |

The commercially available Al-Ti-B ternary master alloy of the chemical composition shown in Table-2 was used for manufacturing the Al- %Ti- %B and its microalloys. High purity zirconium powder was used for manufacturing the Al–3%Zr binary alloy. The crucible and stirring rods used in all the experiments were made of graphite.

2.1.2 Filler and electrode materials
A separate filler made of aluminum with argon as an inert shielding gas, and inconsumable electrode 2.5 mm diameter made of tungsten having conical shape were used in the GTWA welding process.
2.2 Experimental procedures

2.2.1. Preparation of the Al base metal
The commercially pure bundles of the Al wires were pickled in HNO₃ to remove the oxide layers and any other contamination, and then melted in a graphite crucible inside an electric furnace at about 800°C and then poured to solidify in hollow cylindrical brass rods of 10 mm inside diameter and 55 mm external diameter. Finally, the rods were rolled into sheets of 2 mm thickness, 10 mm width and 240 mm length.

2.2.2 Preparation of the binary master and the microalloys
The Al–Zr binary master alloy were prepared by adding the calculated amount of Zr to the predetermined amount of molten aluminum in the graphite crucible at 850°C for Al–Zr binary master alloy, stirred by the graphite rod for one minute and brought back to the furnace for 20 minutes, brought out and stirred again for one minute and finally spread over a thick cast iron plate to solidify in pieces of thickness less than 5 mm. These master alloys were used for preparing the following three different microalloys, with the chemical composition (wt%): Al–0.05%Ti–0.01%B and Al–0.05% Ti–0.01%B–0.1%Zr. Finally, these prepared microalloys together with the commercially pure aluminum specimen were rolled into sheets of 2 mm thickness, 12 mm width and 240 mm length.

2.2.3 The welding process
The tungsten inert gas welding, GTAW, process of the experimental set up shown in figure 1 was used. The single lap joint, figure 2, was used in the welding process.

The welding process started by adjusting the AC current on the welding machine to 30 A which was fixed in welding the different plates. All the specimens were welded using a fixed rate of the shielding gas, constant welding speed, which was calibrated with respect to the motor speed, 0.6 cm/sec, and the current was 30 Ampere AC. The aluminum welding electrode tip is held perpendicular to the welding surface at 5 mm from the workpiece surface. The torch was held perpendicular to the surface of the workpiece and started to heat the starting point of the weld by moving the torch in a circular motion. Once the pool of the molten metal has become bright the torch is ready to be moved along the required weld line.
2.2.4. Hardness testing
The Vicker's microhardness survey were carried out by taking the average of ten values along the HAZ and away from it along the base metal regions, using Digital microhardness tester (model HWDM-3).

2.2.5. Microstructural examination
One specimen of the Al base metal and of each of its microalloys were cut, hot mounted in bakelite ground by different grit size and polished with 1 micron diamond paste. Finally were etched using an etchant of the composition: 1.5% HCl acid, 2.5% HNO₃, 0.5% HF acid and 95.5% H₂O ready for grain size and microstructural examination. The photomicrographs were taken on the HAZ region and on the base metal, away from the HAZ regions as shown in figure 3.

3. Results and discussion
In this section the results are discussed with reference to the effect of addition of either Ti-B or Zr or with Al without addition of any grain refiner. The results and discussion will be dealt with, for welding of Al with each of its microalloys namely Al-Ti-B, Al-Zr and Al-Ti-Bi-Zr under three headings: First effect on the grain size and second on the hardness and third on the soundness of the weld in the HAZ and in the base metal regions. Also the effect of these grain refiners on the weldability of the three aluminum microalloys together; Al-Ti-B with Al-Ti-B, Al-Zr with Al-Zr and AL-Ti-Bi-Zr with Al-Ti-B-Zr as compared to the welding of Al with Al under the above three mentioned headings in HAZ and in the base metal regions, is also presented and discussed.

3.1. Effect of addition of Ti+B and Zr to Al on its grain size
3.1.1. Effect of welding Al with its microalloys on grain size
It can be seen from the histogram of Fig.4 that the addition of Ti-B to Al on its weldability resulted in 31.25% decrease of its grain size in the HAZ region whereas addition of Zr alone did not affect the grain size in this region. However, addition Ti-B and Zr alone resulted in more increase than Ti-B alone being 37.5% which indicates that their addition is not additive. This agrees with previous findings[1]. Similarly, addition of either Ti-B or Zr to Al in the base region either alone or together resulted in decrease of the grain size in the base. The maximum is in case of addition of both of them together being 38.46%, and followed by Zr addition alone, 26.15%

3.1.2 Effect of Welding Al with its Microalloys on Grain Size
It can be seen from the histogram of figure 4 that the addition of Ti+B or Ti-B + Zr to Al has resulted in decrease of 36.36% in grain size in the HAZ whereas addition of Zr alone did not affect the grain size in this region as compared to the Al with Al. However, addition of both of them together resulted in slight decrease in the HAZ when compared to Ti+B addition alone, only 10%. Furthermore, it can also be seen from figure 4 that in the base metal away from HAZ, addition of Ti+B or Zr either alone or together resulted in increase of the grain size as compared to the HAZ of each combination.
Comparing the grain size in the base of welding Al with Al or Al with its microalloys Al-Ti-B, Al-Zr and Al-Ti-B-Zr, it can also be seen from Figure 4 that there is high increase in the grain size when compared to the HAZ. However, when comparing the grain size of the base metal (away from HAZ), between welding Al with Al or with its microalloys, it can be seen there is decrease in the welding of Al with the microalloys. The maximum decrease is 40% in welding of Al with Al-Ti-B-Zr microalloy, 18.4% decrease in welding Al with Al-Ti-B. The fine grain size in the HAZ for welding Al with Al or any of its microalloys Al-Ti-B, Al-Zr and Al-Ti-B-Zr is due to the very high temperature in the HAZ as compared to the base region away from welding Al with the HAZ. However, the decrease of the grain size of the three Al microalloys as compared to Al in the base region is attributed to the refining effect of Ti-B, Zr or Ti-B + Zr when added to Al melt prior to the welding process. This is explicitly illustrated in the photomicrographs of Figure 5.
3.1.3 Effect of welding Al microalloys together on grain size

It can be seen from the histogram of Figure 6 that the grain size in the HAZ and base metal for welding aluminum microalloys together resulted in great reduction in grain size as compared with welding Al with Al being greater reduction in the base metal, for example about 86% in the base metal compared to 37.5% in the HAZ. This may be due to the grain refinement of the two welded microalloys Al-Ti-B prior to welding, as the HAZ is a combination of both welded strip made of Al-Ti-B. However, welding Al-Zr with Al-Zr did not affect the grain size in the HAZ as compared to the grain size in the HAZ of Al with Al (16 microns). Where a pronounced poisoning (larger grain size) in the base metal is indicated, (from 65 to 80), about 23%. Regarding welding Al-Ti-B-Zr with Al-Ti-B-Zr, i.e. when both Ti and Zr are added together, it produced slightly better refinement than in the case of Al-Ti-B with Al-Ti-B, in the HAZ and no difference in the base metal respectively. This is explicitly illustrated in the photomicrographs of Figure 7 a, b, c, d and a', b', c', d' in the HAZ and base metal respectively.

![Figure 6. Effect of Ti and Zr addition on the grain size in the HAZ and base metal of welding Al with Al, Al-Ti-B with Al-Ti-B, Al-Zr with Al-Zr and Al-Ti-B-Zr with Al-Ti-B-Zr microalloys.](image)

![Figure 7. a, b, c, d and a', b', c', d' at HAZ and base metal respectively for welding Al and its microalloys together](image)
3.1.4 Effect of welding Al with its microalloys on microhardness
The histogram of figure 8 shows that the addition of Ti+B or Zr either alone or together to Al on its hardness welding, resulted in decrease of its Vicker's microhardness in the HAZ region. The maximum decrease is 37.5% in case of welding Al with Al-Ti-B-Zn followed by welding Al with Al-Ti-B-Zr and the minimum decrease in (13%) when. The decrease in hardness is attributed to the grain refinement effect and the existence of the intermetallic phases in the Al matrix and to the softening effect caused by the high temperature in the HAZ region. Regarding the effect on the hardness in the base (away from HAZ) it can be seen that there is relatively very slight increase in case of Ti+B and pronounced increase 26.3% in case of welding Al with Al-Ti-B-Zr and no effect in case of Al with Al-Zr.

3.1.5 Effect of welding Al microalloys together on microhardness.
The histogram of figure 9 shows that welding the identical microalloys Al-Ti-B, Al-Zr and Al-Ti-B-Zr together resulted in decrease of their hardness both in the HAZ and the base metal regions when compared with the hardness of the corresponding regions of Al with Al and its microalloys with the following decrease percentages in the HAZ 42, 38.6 and 39.7 for Al-Ti-B with Al-Ti-B, Al-Zr with Al-Zr and Al-Ti-B-Zr with Al-Ti-B-Zr respectively and the following decrease percentages in the base metal region: 12.3, 8.8 and 14.4 respectively. This is also attributed for the grain refinement of these microalloys prior to welding. The histogram of Fig. 9 indicates that there is slight difference between the hardness of welding the microalloys Al-Ti-B with Al-Ti-B, Al-Zr with Al-Zr and Al-Ti-B-Zr with Al-Ti-B-Zr in HAZ or the base regions. The maximum difference is 6.1 % between Ti and Ti + Zr addition in the HAZ in the base regions respectively. However, a pronounced difference exists in the hardness when comparing the welding of the microalloys with that of Al with Al as shown in figure 9 or with welding of Al with Al-Ti-B, Al-Zr and Al-Ti-B-Zr, as illustrated in figure 8.

Figure 8. Effect of Ti+B and Zr addition on the hardness in the HAZ and base metal of welding Al with its microalloys.
4. Conclusions

From the investigation carried out in this Paper, the following points are concluded:

- Addition of Ti+B or Zr either alone or together on the weldability of Al resulted in decrease of the grain size both in the HAZ and base regions when welding Al with Al-Ti-B, Al-Zr and Al-Ti-B-Zr as compared to welding of Al with Al except when welding Al-Zr with Al-Zr in the base region.

- Addition of Ti+B or Zr on the weldability of Al resulted in pronounced decrease in the hardness of the HAZ region for welding Al with Al-Ti-B, Al with Al-Zr and Al with Al-Ti-B-Zr and increase in the base metal except when welding Al with Al-Zr as compared to welding of Al with Al. Similarly in hardness in the HAZ but increase the base metal region for welding Al-Ti-B with Al-Ti-B and Al-Ti-B-Zr with Al-Ti-B-Zr and slight decrease in Al-Zr with Al-Zr.

- Effect of addition of Ti, Zr either alone or together on the weldability of aluminum resulted in sound weld: more homogeneous with less voids and segregation, finer grain size and lower hardness both in the HAZ and base metal regions.

5. References

[1] Zaid A.I.O. Review of the grain refinement of aluminum and its alloys, (ISAM7 Pakistan, 2001).
[3] Kou S. 2003 Welding Metallurgy 2nd ed. John Wiley and Sons Inc.
[4] Din EN 439 1995 Shielding Gases for Arc Welding and Cutting.
[5] Simpson R P. 1977 Weld Journal 56 67-72.
[6] Gerland G. J.1974 Metal Construction 6 121-128.
[7] Prasad R.S. 2001 Proceedings of National Advances in Materials Processing Annamalai Nagar, India 176-196.
[8] Kou S. and Le Y. 1986 Weld Journal 65 65-70.
[9] Madusudhan R. G., Gokhale A. A. and R.K. Prasad R.K. Weld microstructure Refinement in a 144 Grade Al-Lithium Alloy 32 4117-4121.
[10] Tseng C. F., Savage W. F. 1971 Weld J 50 777-785.
[11] Kumar A., Sundarrajans. 2009 Materials and Design 30 1288-1297.
[12] Kim I. S., Son J. S., Kim I. G. , J.Y. Kim J.Y., Kim O. M. 2003 Journal of Material Processing Technology 136.
[13] Cary H. B.1984 Modern Welding Technology New Jersey: Prentice Hall.
[14] Davis J. R. 1994 ASM Specialty Handbook: Aluminum and Aluminum Alloys, Ohio: ASM International Materials Park.
[15] Tony A 2002 The American Welder: Weld Journal 64 77-80.
[16] Kumar A, Sundarraj S. 2006 Mater. Manufacturing Process 21 789-793.
[17] Sundaresan S, Janaki: R. G. H. 1999 Science Technol Weld Joining 4 151-160.
[18] Kumar A., Nageshwar R.G.V.S., Sundarraj S. 2007 Int. J. Logic Intell. System 1 85-94.