MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SIMULATED Al-Mg-Zn WELD METAL MODIFIED WITH Sc AND Zr

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ABSTRACT
A comprehensive analysis of simulated weld metal microstructures, tensile properties, and aging characteristics has been performed for high purity Al-Mg-Zn ternary alloys treated with scandium and zirconium. These alloys showed significant aging response, with increases in strength proportional to total alloy content. The ductility decreased with total alloy content, but remained particularly high for the high Zn/Mg alloy variants. Scandium served as an effective grain refiner and, in addition, resulted in a modified (more elongated) shape of eutectic constituents. The implication of these findings with regard to target weld metal compositions and future filler alloy development are briefly discussed.

Keywords: *aluminium-magnesium-zinc-scandium, weld metal, alloying, tensile properties*

INTRODUCTION
In order to make welded aluminium structures more competitive with steel, it becomes desirable to improve upon the mechanical efficiency of welded joints. Extrusion alloys capable of post-weld natural aging, such as alloy 7108, have become attractive for use in ship decking and superstructures in locations where direct exposure to sea water can be avoided. However, the mechanical joint efficiency of an aluminium 7108 weldment (expressed in terms of percentage yield strength) is only about 50-60% [1]. This clearly limits the ability of the ship designer to make full use of the inherent strength of these extruded base materials. Because the weld metal is typically the weakest part of the joint, there is impetus for developing new welding filler alloys capable of providing improved weld metal strength.

The filler alloys, which are available commercially, consist primarily of aluminium-magnesium binary alloys which rely upon magnesium in solid solution for strengthening. Following welding, there may also be an additional contribution to strength from precipitation hardening (i.e. natural aging) as a result of dilution with the base metal.

The problem of interest here is to investigate the use of more highly alloyed fillers which, following welding, might provide even higher levels of precipitation hardening. Previous studies have demonstrated that zinc containing filler metal result in higher weld metal tensile strengths [2]. However, in the case of welds made on 7108, the use of more highly alloyed (zinc containing) fillers may also result in a greater tendency for hot cracking [2, 3, 4].

The approach taken in the present investigation has been to characterize the mechanical properties of high purity Al-Mg-Zn alloys over a broad spectrum of compositions. These alloys were treated with small amounts of alloy modifiers (zirconium and scandium) believed to improve weldability through grain refinement [5, 6]. All of the alloys examined in this study were in the form of castings, taken to simulate weld metal microstructures. The weld metal was simulated b means of rapid cool "chill" casting, where cast tensile bars were produced in copper book-molds.

EXPERIMENTAL

Test Matrix

Alloy compositions were selected along three different Zn/Mg ratio variants; one variant along the quasi-binary line (Zn/Mg=2.5) and two variants on either side of it (Zn/Mg=1.5 and 4.5 respectively). Within each variant, the total alloy content (Mg+Zn) was also varied as shown in Table 1. Each of these alloys were treated with 0.015 weight percent Zr plus 0.30 weight percen Sc. Also, an additional series of alloys were produced along the quasi-binary variant (Zn/Mg=2.5) free from Sc additions, but still containing 0.15 weight percent Zr.

Table 1: Nominal Compositions of Experimental Al-Mg-Zn Alloys (in wt.%).

Alloy	1	2	3	4	5	7	8	9	10	11	12	13	14	15	16	17	18
Mg	2.00	2.40	2.80	3.20	3.60	1.43	1.71	2.00	2.29	2.57	2.86	0.91	1.09	1.27	1.45	1.64	1.8
Zn	3.00	3.60	4.20	4.80	5.40	3.57	4.29	5.00	5.71	6.43	7.14	4.09	4.91	5.73	6.55	7.36	8.1
Mg+Zn	5	6	7	8	9	5	6	7	8	9	10	5	6	7	8	9	10
Zn/Mg	1.5					2.5						4.5					
variant	low Zn/Mg					quasi-binary						high Zn/Mg					

Alloy Preparation

Alloys were prepared by first casting 3 different Al-Mg-Zn master alloys (i.e. 1 master alloy fo each alloy variant). This was done by introducing preweighed amounts of magnesium and zinc into molten aluminium (99.999% pure). Individual alloys in Table 1 were prepared by taking preweighed amounts of these master alloys together with a scandium master alloy (2 wt.% Sc) and a zirconium master alloy (10 wt.% Zr), and adding this mixture to molten aluminium (99.999% pure) Master alloys were weighed to the nearest half gram. The zirconium master alloy was added just minutes before casting to minimize fading effects (i.e. aluminide dissolution). Alloys were prepared in 500 gram heats and were degassed by means of argon sparging prior to casting.

For each heat of alloy prepared, three cylindrical bars were cast in a copper mold. The dimensions of these cast cylinders, 15 mm dia. x 100 mm long, were suitable for machining cylindrical tensile bars for mechanical testing: 7.5 mm diameter x 25.4 mm gage. Specimens from these castings were also used for metallographic examination. After each casting operation, the copper mold was cooled to room temperature prior to the next casting, to ensure consistent cooling conditions. Immediately following casting, all parts were removed from their molds and air cooled Emission spectrographic analysis of the alloys showed compositions to be within 6 percent of nominal. Impurities were found to reside at low levels averaging 179 ppm Si and 19 ppm Fe (by wt.).

RESULTS

Natural Aging

Shown in Figure 1a, b, and c are the natural aging curves for each of the three alloy variants of Table 1. For each of the alloy variants, the peak hardness is found to increase with total alloy content. Both the range of hardness values and the maximum hardnesses achieved were found to increase with higher Zn/Mg ratios. The largest portion of the hardness gained during natural aging occurred within the first 300 hours of aging.

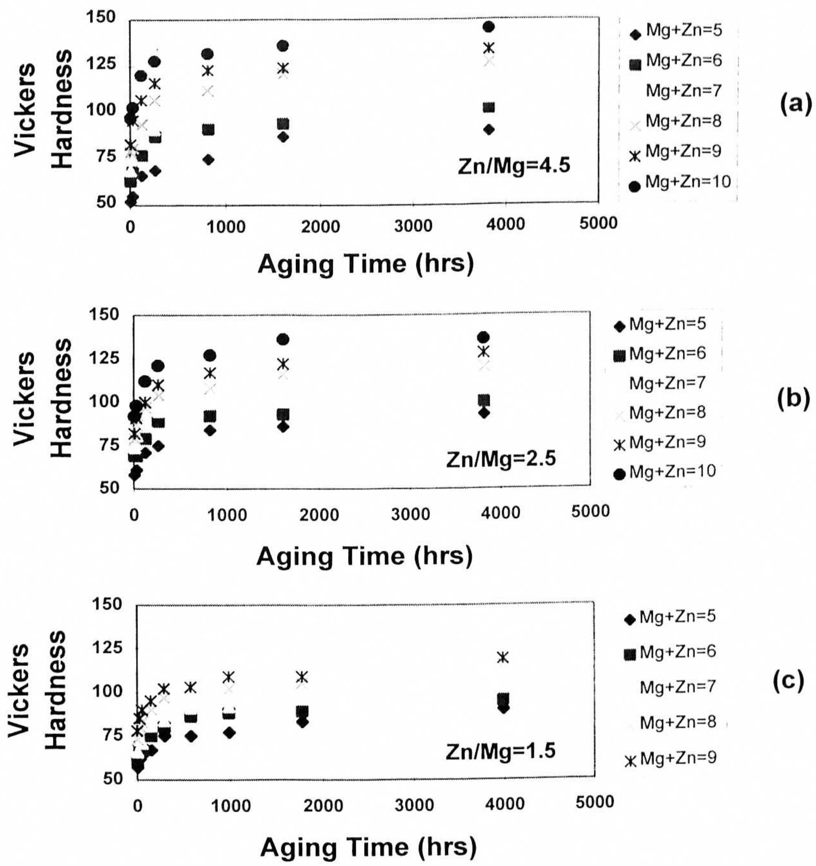

Figure 1: Natural aging curves for simulated Al-Mg-Zn weld metal with a) Zn/Mg=4.5, b) Zn/Mg=2.5 and c) Zn/Mg=1.5.

Tensile Properties

Tensile tests performed after 9-11 weeks of natural aging revealed that the yield strength increases linearly in proportion to total alloy content as shown in Figure 2. Here it is seen that the Zn/Mg ratio is less important than the total alloy content, although the high Zn/Mg variant demonstrates slightly higher properties. Ductility, on the other hand, decreases with total alloy content, as shown in Figure 3, where the high Zn/Mg variant exhibits the highest ductility.

True stress-strain flow curves for these alloys are compared in Figure 4, but only up to a strain of 1 percent (the extensometer was removed beyond this point to avoid damage). Included also is the flow curve for the weld metal of a normal 7108 weldment, made using 5356 filler wire [7]. It is observed that about half of the experimental alloys studied fall above this baseline level.

Strain hardening rates, obtained from the data in Figure 4, are compared in Figure 5. These rates are observed, in general, to increase with total alloy content and are particularly high for the high Zn/Mg variants. However, since the level of strength attained for any given alloy is influenced by both its yield strength and its strain hardening rate, it is convenient to rank the different alloys in terms of their flow stress evaluated at some common strain. As shown in Figure 6, the flow stress at 1 percent strain is found to increase linearly with total alloy content. Only a small effect of the Zn/Mg ratio is observed.

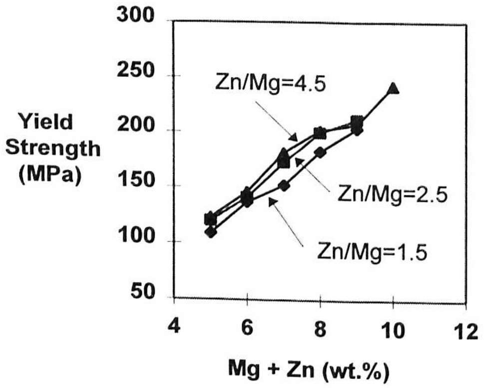

Figure 2: Yield strength of simulated Al-Mg-Zn weld metal showing effect of total alloy content (Mg+Zn).

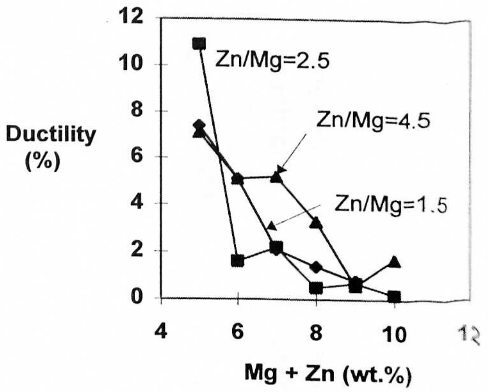

Figure 3: Dutility of simulated Al-Mg-Zn weld metal showing effect of total alloy content (Mg+Zn). 25mm gage

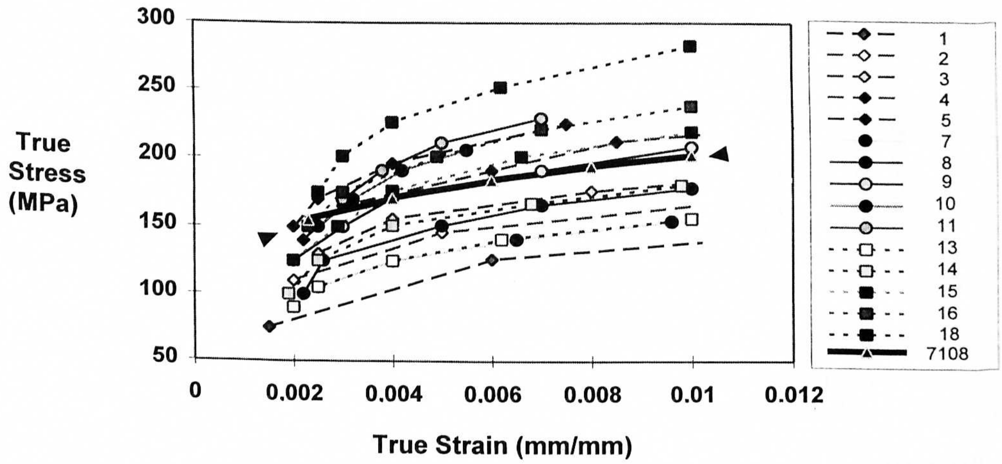

Figure 4: True stress-true strain flow curves comparing simulated Al-Mg-Zn weld metal.

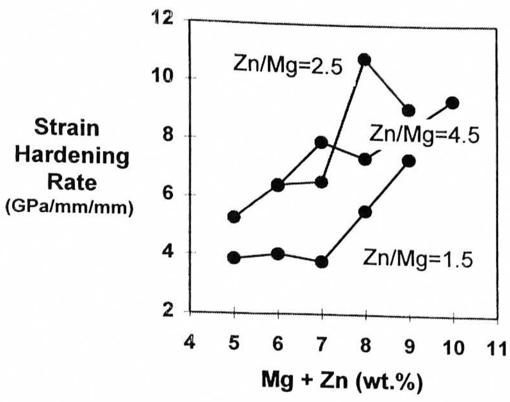

Figure 5: Strain hardening rate of simulated Al-Mg-Zn alloys showing effect of total alloy content (Mg+Zn).

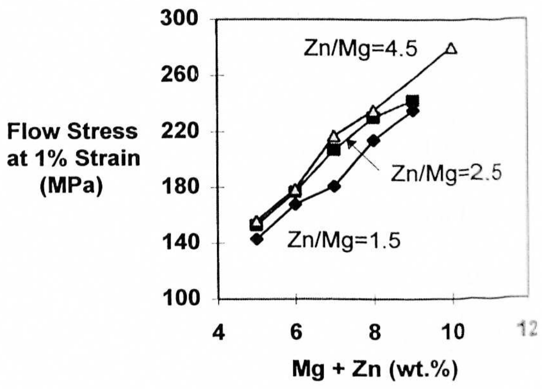

Figure 6: Flow stress for simulated Al-Mg-Zn weld metal showing effect of total alloy content (Mg+Zn).

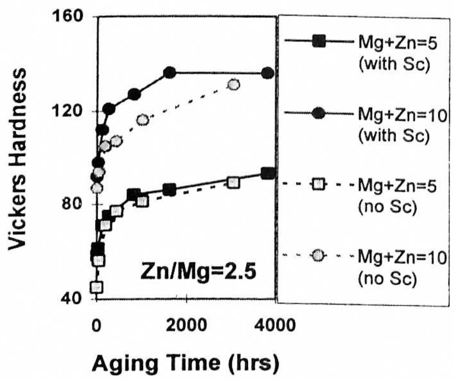

Figure 7: Comparison of natural aging curves for simulated Al-Mg-Zn weld metal (Zn/Mg=2.5) with and without Sc.

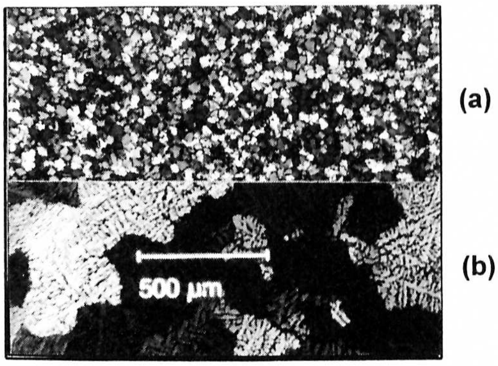

Figure 8: Grain structure for simulated Al-Mg-Zn weld metal comparing alloy #9 both a)with Sc and b) without Sc.

Aging curves for two different alloy contents are compared in Figure 7, both with and without Sc. Sc was found to improve the strength of the Zn/Mg = 2.5 variant, but only at high alloy contents. This observation was confirmed by tensile tests, where, for example, the yield strength of alloy number 11 was found to be 10 percent higher than its Sc-free counterpart.

Microstructure

The interdendritic eutectic was observed to possess a filigree substructure as has been reported for similar type alloys [8]. Its composition, as determined from energy dispersive X-ray analysis, was found to vary from an atomic Zn/Mg ratio of 1.8 to 2.6 to 4.2, increasing with Zn/Mg content of the alloy, respectively. This suggests the possibility that the $Mg_3Zn_3Al_2$ (T-phase) may be present in the low Zn/Mg variant, but is replaced by $MgZn_2$ (η-phase) and Mg_2Zn_{11} in the higher Zn/Mg variants [9]. The amount of eutectic second phase present was observed to decrease with higher Zn/Mg ratios. Sc was found to segregate to the eutectic and also to particles rich in Zr (i.e. possible grain nucleation sites). In the absence of Sc, these eutectic particles are spherical in shape, but they become distinctly elongated when Sc is added. Sc was also found to serve as an effective grain refiner, as indicated in Figure 8 where alloy number 9 is compared with its Sc-free counterpart. The average grain size is reduced from 270 microns down to 29 microns.

DISCUSSION

It is apparent that improvements in weld metal strength can be achieved by increasing the total alloy content and the Zn/Mg ratio. Judging from the strong response to natural aging, it is clear that the observed strength improvements are primarily the result of precipitation hardening. Higher alloy contents must result in greater amounts of solute in solution following solidification and, hence, a greater volume fraction and finer distribution of precipitates upon natural aging. The lower amount of eutectic generated in the high Zn/Mg alloys explains both their higher strength (more solute in solution) and superior ductility (fewer sites for crack initiation and propagation).

The specific role that Sc plays in grain refinement and precipitation is uncertain. Sc is believed to form a high temperature (~660°C) eutectic with aluminium [10] which, conceivably, could provide nucleation sites for new grains. Whether or not the presence of Zr is also required for grain refinement to occur has not yet been determined. The effect of Sc on improving strength may, in part, be due to grain refinement, but could also involve an interaction with precipitation reactions. Contradictory studies performed on simulated 7108 weld metal, of commercial purity, have shown that Sc can actually lower the flow stress [11].

One important task remaining is to define the most desirable tensile properties (i.e. flow stress + ductility) for the weld metal. Insight into this question has been provided by the finite-element modeling work of Zhang [7], used to predict the strain distribution in cross-weld tensile tests. His work suggests that the true stress-strain curve of the weld metal must intersect the corresponding flow curve of the adjacent material (i.e. HAZ and base metal) in order to transfer strain to its surroundings. Thus, the weld metal must have at least sufficient ductility to achieve this critical flow curve intersection. The level of this critical flow stress will be determined by the properties of the base metal, HAZ, and weld metal and is a topic for on-going research.

Other questions also remain regarding the weldability of these alloys. The use of higher Zn containing weld metal is known to result in practical problems including puddle control and hot cracking. The problem with puddle control, which results from poor fluidity, can be overcome with the use of helium-argon welding gas and higher welding currents [12]. Problems with hot cracking can be avoided by grain refinement through additions of Sc plus Zr or Tibor [11].

CONCLUSION

The natural aging potential and the tensile properties of simulated Al-Mg-Zn weld metal have been shown to increase proportionally with total alloy content. The high Zn/Mg alloy variant showed slightly higher strength and ductility performance. Sc, when present together with Zr, was found to both refine the solidification grain structure and modify the morphology of the interdendritic eutectic. The presence of Sc was also shown to result in higher strengths for the Zn/Mg=2.5 variant at high alloy content. Strength improvements over traditional 7108/5356 weld metal have been demonstrated.

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REFERENCES

[1] A.O. Kluken and B. Bjørneklett: Welding J., 76(1997), 39-44.
[2] F.E. Gibbs: Welding J., 45(1996), 445s-453s.
[3] W. Patterson and S. Engler: Aluminium, 35(1959), 124-130.
[4] M.G. Mousavi, C.E. Cross, Ø. Grong and M. Hval: Sci. Tech. Weld. Join., 2(1997), 275-278.
[5] F. Matsuda, K. Nakata, J.Shimokusu, K.Tsukamoto and K. Arai: Trans. JWRI, 12(1983), 81-87.
[6] B. Irving, Welding J., 76(1997), 53-57.
[7] Z. Zhang: SINTEF Rpt. STF24 F97353, Trondheim, Norway (1997).
[8] P. Droenen and N. Ryum: Met. Trans., 25A(1994), 521-530.
[9] H. Liang, S.L. Chen and Y.A. Chang: Met. Trans., 28A(1997), 1725-1734.
[10] R.W. Hyland: Met. Trans., 23A(1992), 1947-1954.
[11] M.G. Mousavi and C.E. Cross: SINTEF Rpt. STF24 F97712, Trondheim, Norway (1997).
[12] J.A. Liptak: Welding J., 45(1966), 561s-568s.