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Microstructure and properties of Al-Mg-(Sc, Zr) welded joint①

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Abstract: Mechanical properties and microstructure of Al-Mg-(Sc, Zr) welded joint prepared by manual labor melt inert gas(MIG) welding method using Al-Mg and Al-Mg-Sc weld wire as filling materials were studied comparatively. The results show that the apparent recrystallization does not happen in heat-affected zone. It proves that Al-Mg-(Sc,Zr) alloy has a high capability of resistance to welding heat-soften. Using Al-Mg-Sc welding wire as filling material can obviously refine the grains of weld seam and improve its strength. The layer of small equal-axe grains in fusion area improves the joint strength between welded metal and base metal. The coefficients of welded joints when Al-Mg-Sc and Al-Mg welding wire are used as filling material are greater than 0. 90, respectively. The yield strength of welded joints with Al-Mg welding wire is only 187 MPa, one is as high as 287 MPa with Al-Mg-Sc welding wire, thus the working strength of the welded unit is greatly improved.

Key words: Al-Mg-Sc alloy welding; welding wire; microstructure and properties of welded seam

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1 INTRODUCTION

Al-Mg-Sc alloy is a new structural material used in aerospace, which owns many advantages, such as high strength, erosion resistance, good welding property and low sensitivity of heat crack.[1-6]. Al-Mg-Sc alloy has been a popular research of high-performance aluminum. However, few researches studied on the relationship between welding microstructure and properties of this alloy. In this paper, Al-Mg and Al-Mg-Sc welding wires were used as filling materials, Al-Mg-(Sc, Zr) alloy plates were welded by MIG welding method. The influence of Sc on microstructure and mechanical properties of weld joint were investigated by optical microscope, microhardness tester and transmission electron microscope.

2 COMPOSITION OF MATRIX METAL AND WELDING WIRE

Chemical composition of Al-Mg-(Sc, Zr) alloy plates (base metal), Al-Mg-Sc and Al-Mg alloy welding wire in experiment are shown in Table 1. Plates were welded by MIG welding method. The welding parameters are shown in Table 2. Before welding, the surface treatment should be performed for welding wire and welded plates, the surface of welding area was washed by acetone and alcohol, after that, was scrubbed by steel brush, the welding was finished in 8 h.

Table 1 Chemical composition of welding wire (mass faction, %)

	Mg	Sc+Zr	Cr	Ti	Al
Al-Mg-Sc alloy plates(base metal)	5. 8 - 6. 8	0. 2 - 0. 4	—	—	Remains
Al-Mg-Sc alloy welding wire	6. 2 - 6. 8	0. 3 - 0. 5	0. 05 - 0. 20	0. 02 - 0. 05	Remains
Al-Mg alloy welding wire	6. 2 - 6. 8	Zr: 0. 1 - 0. 2	0. 05 - 0. 20	0. 02 - 0. 05	Remains

Table 2 Parameters of MIG welding

Thickness of welded plates/ mm	Tungsten electrode diameter/ mm	Diameter of welding wire/ mm	Diameter of muzzle/ mm	Welding current/ A	Argon flow/ ($L \cdot min^{-1}$)
2	3 - 4	3	6 - 9	90 - 110	11 - 13

3 EXPERIMENTAL RESULTS

3. 1 Mechanical properties of welded joint

3. 1. 1 Vickers-microhardness distribution of welded joint

Vickers-microhardness were tested in the welded metal and heat-affected zone of Al-Mg-(Sc, Zr) welded joint prepared by manual labor TIG welding method using Al-Mg and Al-Mg-Sc welding wire as filling materials. Vickers-microhard-

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ness distribution of the different distance from welded centre line is shown in Fig. 1. It is easy to see that the distribution regularities of two type welded joints are similar, the centre of welded seam has the lowest hardness, the hardness become higher gradually when it transits from welded center to base metal. We can see the width of heat-affected zone(HZA) is 4 mm by hardness distribution. The hardness of the welded center using Al-Mg-Sc alloy as filling material is greater than that using Al-Mg alloy.

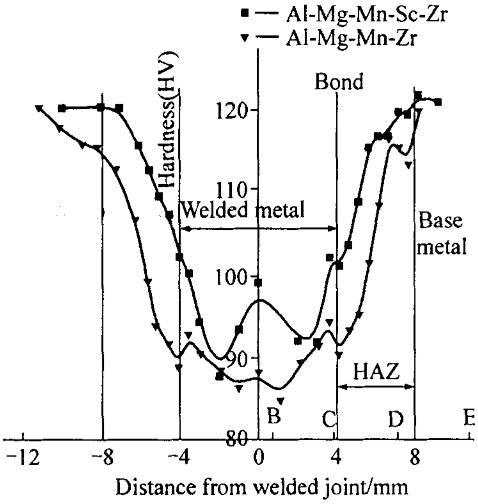

Fig. 1　Vickers-microhardness distribution of welded joint

3. 1. 2　Tensile property

Mechanical properties of welded joints with Al-Mg and Al-Mg-Sc alloy welding wire are shown in Table 3. The data from Table 3 show that the tensile strength of Al - Mg - (Sc , Zr) alloy plates is about 380 MPa, the elongation is greater than 7%, the coefficient of welded joints are both greater than 0. 90. Using the former, the yield strength of the joint is merely 188 MPa; while using the latter, the yield strength is 287 MPa, moreover, the tensile strength also increases and the coefficient of welded joints achieves 0. 91.

Table 3　Mechanical properties of welded joint

Filling welding wire	Mechanical properties of tensile			Coefficient of welded joints	Cracked position
	σ_b/MPa	$\sigma_{0.2}$/MPa	δ/%		
Al-Mg-Sc	383	287	7. 6	0. 91	Fusion zone
Al-Mg	379	188	7. 5	0. 90	Fusion zone

3. 2　Microstructure of welded joint

When Al-Mg-Sc alloys were used as filling material, the optical microstructure of the weld metal zone, fusion area, heat-affected zone and base metal of welded joint of Al-Mg-(Sc, Zr) alloy plates are shown in Fig. 2. The observed positions of Figs. 2(b), (c), (d) and (e), respectively corresponds with the B, C ,D and E points in Fig. 1. There are the cast-structures of both thin and coarse equal-axe crystals in the weld melt zone (Figs. 2(a) and (b)); there are not the columnar crystals of the unit crystallization at the boundary of the welded centre line and fusion area, which usually appears in these area, but a quite layer of equal-axe crystal (Fig. 2(c))

Using Al-Mg alloy wire as filling material, the optical microstructure of the welded metal zone and the fusion area of welded joint of Al-Mg-(Sc, Zr) alloy plates are shown in Fig. 3. Compared with

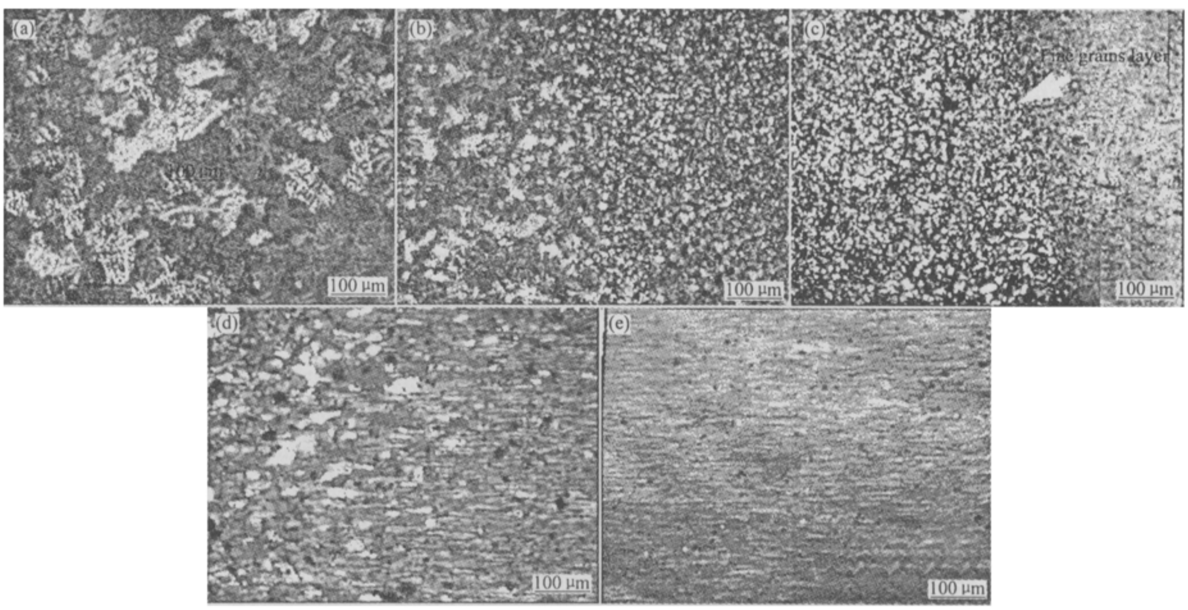

Fig. 2　Microstructure of welded joint of Al-Mg-(Sc, Zr) alloy plants welded by using Al-Mg-Sc welding wire as filling materials

(a)—Coarse gains zone of welding area; (b)—Welding zone; (c)—Fusion area; (d)—Soft zone in HAZ; (e)—Base metal

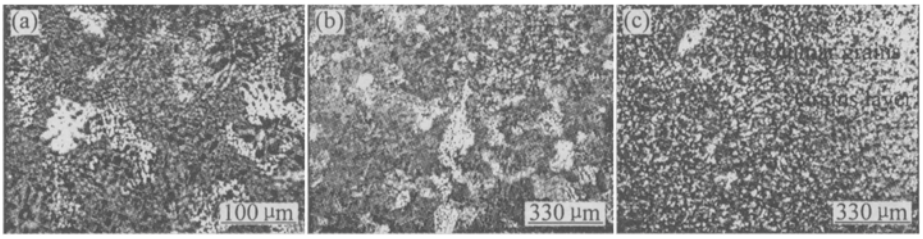

Fig. 3 Microstructure of welded joint of Al-Mg-(Sc, Zr) alloy plants welded by using Al-Mg welding wire as filling materials
(a)—Coarse gains zone of welding area; (b)—Welding zone; (c)—Fusion area

Figs. 2(a), (b) and Figs. 3(a), (b), respectively, it is found that the cast structures of the welded zone were obviously refined by adding minor Sc. The columnar crystals which grows with the direction of radiation were observed in welded joint of Al-Mg welding wire (Fig. 3(c)), which are the typical microstructures of the united-crystallization, however, there are not the columnar crystals but a layer of equal-axe crystals (Fig. 2(c)) .

Adopting Al-Mg-Sc welding wire, the transmission electron microstructure of the heat-affected zone and weld zone of the welded joints are shown in Fig. 4. There are non-recrystallizing cold-forming fibrous tissues, initiate recrystallized grains and quite recrystallized grains in Fig. 4(a). From Fig. 4(b), primary $Al_3(Sc,Zr)$ compound particles precipitated in the weld zone during the cooling is horse-shoe shape, which shows the coherency between the particles and base.

4 DISCUSSION

4.1 Grain refining effect of minor Sc and Zr results in strengthening of welding metal

When adopting Al-Mg-Sc welding wire as filling materials, some second-phase particles, such as Al_3Sc、Al_3Zr、$Al_3(Sc,Zr)$ and $Al_3(Ti,Sc)$, are formed in the non-equilibrium solidification process of welding molten bath. Crystal lattice patter and dimensions of these particles are extremely similar to that of the matrix, the dismiss among them is small. These primary phase particles can be cores of heterogeneous nucleation, and refine the gains of welded seam. The welding melt zone was filled with refining equal-axe crystal and several coarse dendritic crystal(Fig. 2(b)). When it is welded by Al-Mg-Sc alloy welding wire, the size of grain in welding melt zone is 20 – 60 μm , and the area of coarse grains zone correspondingly decreases(Fig. 2 (a), (b)). While the size of grain in welding melt zone is 80 – 100 μm(Figs. 3(a),(b)).

4.2 Improvement of consistency between welded metal and base metal by Al-Mg-Sc alloy welding wire

The composition's design of Al-Mg-Sc alloy welding wire is basically same as that of Al-Mg-(Sc,Zr) alloy plates. Considering the loss of magnesium in the process of welding, we increased the content of magnesium. Then addition of minor Ti and Cr is for improving the strength of welded seam by forming some primary phase, such as $Al_3(Ti,Sc)$, Al_7Cr etc. From the optical pictures of microstructure of welded joints, we can see that there is a unique layer of refining equal-axe grains on the edge of weld metal zone, while a thin and unconspicuous layer with the Al-Mg alloy welding wire.

Using Al-Mg-Sc alloy welding wire, the welded metal is near by the base metal firstly solidified, then the minor element Sc and Zr enrich in the liquid phase which is in the front of solid-liquid interface, it can stop shifting of other element atoms and increase the solute concentration and degree of super-cooling. For this, the growth of columnar grains which are formed as united-crystal is restricted. The compound particles, such as $Al_3(Sc,Zr)$, $Al_3(Ti, Sc)$, Al_7Cr, formed from welding wire with a high thermostability, become the core of heterogeneous nucleation, therefore, there is a mass of equal-axe grains but dendritic in this area. While columnar grains which are formed as united-crystal appear in welded joints with Al-Mg alloy welding wire[7-10].

4.3 Characteristic of heat-affected zone in Al-Mg-(Sc, Zr) alloy welded joints

From the microhardness and optical microstructure, the heat-affected soften zone of is narrow (4 mm in manual MIG welding). There is a mass of $Al_3(Sc,Zr)$ second-phase particles in Al-Mg-(Sc, Zr) alloy plates . These particles would coarsen and aggregate under the high temperature

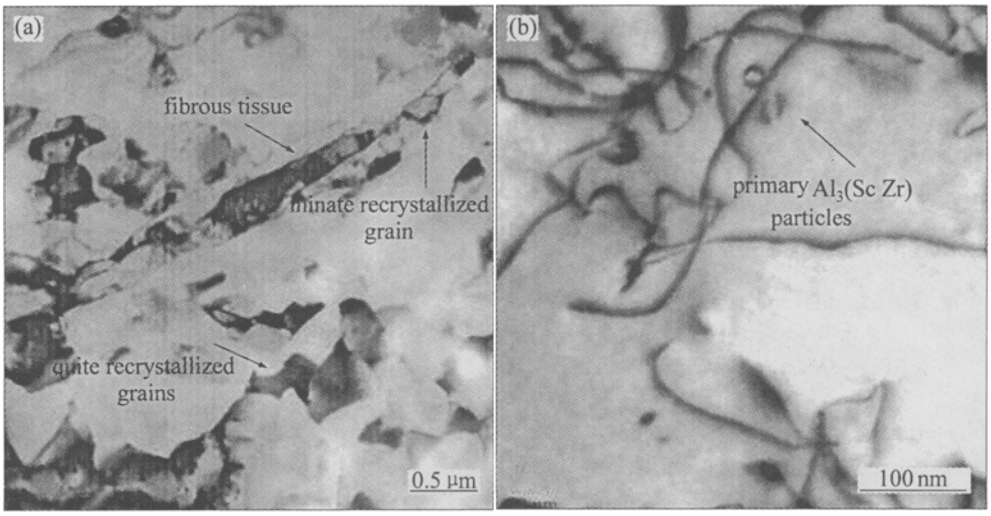

Fig. 4 TEM images of welded joint of Al-Mg-(Sc,Zr) welded by using Al-Mg-Sc welding wire as filling material
(a)—Heat-affect zone; (b)—Welding metal zone

effect of welding thermal cycle. They remain in the matrix to pin the dislocation and sub-boundary, and effectively restrain recrystallization, so remain a lot of cold deformation microstructure[11]. When carrying on the tensile test, Al-Mg-(Sc, Zr) alloy welded joints were broken in the position of the fusion area which was correspondingly soft but heat-affected zone under the condition of strengthen with excess in weld metal zone.

4.4 Yield strength of welded joints

Hall-Pecth formula indicates that the refining of grains remarkably improves the yield strength of the metal[12]. Using the Al-Mg-Sc welding wire as the filling metal, the certain width layer of refining grains can increase the yield strength of welded joints. Otherwise, the effect of Al_3(Sc,Zr) particles pining dislocation and grain boundary also enable to improve the yield strength of welded joints.

Working strength of the welded unit is taken the yield strength as the reference, increasing the yield strength is to improve the working strength. The yield strength of welded joints with Al-Mg-Sc welding wire is 100 MPa higher than that with Al-Mg welding wire, so it greatly improves the working strength of the welded unit.

5 CONCLUSIONS

1) Using Al-Mg-Sc alloy welding wire as filling material, due to the grain refining effect of the Al_3(Sc,Zr), the welded joint microstructure can be refined obviously. So the strength of welded joints is improved.

2) Al-Mg-Sc alloy soldering wire has well consistent ability with the Al-Mg-(Sc, Zr) base alloy. It can form a fine crystalline layer with definite width in the fusion zone by using Al-Mg-Sc alloy soldering wire as filling material. In this way, we can improved strength of the fusion zone or consistent ability between welded joint and backing.

3) the Al_3(Sc,Zr) particle of the base metal of Al-Mg-(Sc, Zr) alloy can effectively depress recrystallize and save lots of cold-forming organizes to improve the welded joint's ability of anti-demineralization.

4) The coefficients of welded joints with Al-Mg-Sc and Al-Mg welding wire as filling material are both greater than 0.90, the tensile strength of Al-Mg-(Sc, Zr) alloy plates is about 380 MPa, the elongation percentage is greater than 7%. However, the yield strength of welded joints with Al-Mg welding wire is only 187 MPa, while it reaches 287 MPa with Al-Mg-Sc welding wire, greatly improve the working strength of the welded unit.

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