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Effects of Sc and Zr on mechanical property and microstructure of tungsten inert gas and friction stir welded aerospace high strength Al–Zn–Mg alloys

Ying Deng [a,b,c], Bing Peng [a], Guofu Xu [b,c,*], Qinglin Pan [b], Zhimin Yin [b], Rui Ye [b], Yingjun Wang [d], Liying Lu [d]

[a] School of Metallurgy and Environment, Central South University, Hunan, Changsha 410083, China
[b] School of Materials Science and Engineering, Central South University, Hunan, Changsha 410083, China
[c] State Key Laboratory for Power Metallurgy, Central South University, Hunan, Changsha 410083, China
[d] Northeast Light Alloy Co. Ltd., Hei Longjiang, Harbin 150060, China

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ABSTRACT

New aerospace high strength Al–Zn–Mg and Al–Zn–Mg–0.25Sc–0.10Zr (wt%) alloys were welded by tungsten inert gas (TIG) process using a new Al–6.0Mg–0.25Sc–0.10Zr (wt%) filler material, and friction stir welding (FSW) process, respectively. Mechanical property and microstructure of the welded joints were investigated comparatively by tensile tests and microscopy methods. The results show that Sc and Zr can improve the yield strength and ultimate tensile strength of Al–Zn–Mg alloy by 59 MPa (23.3%) and 16 MPa (4.0%) in TIG welded joints, and by 77 MPa (23.8%) and 54 MPa (11.9%) in FSW welded joints, respectively. The ultimate tensile strength and elongation of new Al–Zn–Mg–Sc–Zr alloy FSW welded joint are 506 ± 4 MPa and $6.34 \pm 0.2\%$, respectively, showing superior post welded performance. Mechanical property of welded joint is mainly controlled by its "weakest microstructural zone". TIG welded Al–Zn–Mg and Al–Zn–Mg–Sc–Zr alloys reinforced with weld bead both failed at fusion boundaries. Secondary $Al_3Sc_xZr_{1-x}$ particles originally present in parent alloy coarsen during TIG welding process, but they can restrain the grain growth and recrystallization here, thus improving welding performance. For two FSW welded joints, fracture occurred in weld nugget zone. Secondary $Al_3Sc_xZr_{1-x}$ nano-particles almost can keep unchangeable size (20–40 nm) across the entire FSW welded joint, and thus provide effective Orowan strengthening, grain boundary strengthening and substructure strengthening to strengthen FSW joints. The positive effect from Sc and Zr additions into base metals can be better preserved by FSW process than by TIG welding process.

1. Introduction

High-strength thermally strengthened alloys based on the Al–Zn–Mg system are extensively used for fabrication of reliable and lightweight aerospace structures due to their excellent combination of high mechanical property and satisfactory weldability [1–3]. However, with the development of national defense and aerospace industry, it is urgent to develop new aluminum alloys with higher strength and more excellent weld performance to satisfy the requirement of weight saving. Of all microalloying elements used to strength wrought aluminum alloys, the combined additions of scandium and zirconium offer the greatest potential [4,5]. The positive effect is from the formation of coarse primary $Al_3Sc_xZr_{1-x}$ particles which can refine grain structure and extremely fine coherent secondary $Al_3Sc_xZr_{1-x}$ particles with $L1_2$ structure which can effectively inhibit recrystallization and pin dislocations [6–8]. New Al–Zn–Mg–Sc–Zr alloy with higher strength and toughness and better corrosion resistance belongs to a new generation lightweight aerospace structural material [9,10].

The welding of aerospace high-strength Al–Zn–Mg alloys has received renewed attention, because of the need to reduce the high manufacturing costs associated with the fabrication of riveted, or fastened, airframe structures [11,12]. Tungsten inert gas welding process is the most widely used welding technology for aerospace aluminum alloys [13,14]. However, until the past decade the aerospace industry has not seriously considered fusion welding high strength 7000 series aluminum alloys, as an alternative to mechanical fastening, because such alloys have generally been regarded as unweldable. Norman [14,15] and Sundaresan [16]

* Corresponding author at: School of Materials Science and Engineering, Central South University, Hunan, Changsha 410083, China. Fax: +86 731 88877217.
E-mail addresses: csudengying@163.com (Y. Deng), csuxgf66@csu.edu.cn (G. Xu).

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developed new aluminum filler wires added with scandium which can improve the quality of solidification structure produced in fusion zone, reduce weld solidification cracking susceptibility, enhance the weldability and mechanical property of fusion welded joint, thereby those filler materials can be used to produce welds in aerospace 7000 series Al alloys with property levels that are acceptable for many aerospace applications. Currently, existing literature basically focuses on the effects of Sc additions into filler materials on welding performance and the relationship between the property and microstructure of TIG welded joints. However, little attention is paid on the comparative investigation of mechanical property and microstructure of TIG welded joints of high strength Al–Zn–Mg alloys with and without Sc additions.

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a new solid-state joining method and is considered to be the most promising welding technology that can produce low-cost and high-quality joints of high strength aluminum alloys because it does not need consumable filler material and can eliminate some welding defects such as hot cracks and porosity [17,18]. One of the most important advantages of this welding technology is that there is only a slight loss in mechanical property as compared to the base materials. Therefore, it is of great significance to join the high strength aluminum alloy with friction stir welding technology to achieve the goal of higher strength of the integral structures. The fatigue performance [19], corrosion resistance [20] and mechanical property [21] of FSW welded high strength aluminum alloys have attracted much attention all over the word. Nonetheless, to the best of authors' knowledge, the investigation about the effects of Sc and Zr microalloying additions on the microstructure and mechanical property of aerospace high strength Al–Zn–Mg alloy FSW welded joints is very limited.

In this paper, we aim to weld aerospace high strength Al–Zn–Mg and Al–Zn–Mg–Sc–Zr aluminum alloys by TIG and FSW processes. Based on this, the mechanical property and microstructures of four welded joints will be investigated comparatively to reveal the effects of welding processes and Sc and Zr microaloying effects on welding performance and microstructure of aerospace high strength Al–Zn–Mg alloys. The purpose of this paper is to provide theoretical and experimental basis for engineering design and application of new aerospace high strength aluminum alloys and new welding technology.

2. Materials and methods

Two kinds of 2 mm-thick aged Al–Zn–Mg base alloys (T6 temper) with and without Sc and Zr addtions were provided by Northeast Light Alloy Co., Ltd. Their chemical compositions are as follows: Al–5.40Zn–1.98Mg–0.35Cu–0.33Mn–0.10Si–0.20Fe (Al–Zn–Mg) and Al–5.39Zn–2.00Mg–0.35Cu–0.25Sc–0.10Zr–0.32Mn–0.10Si–0.20Fe (Al–Zn–Mg–Sc–Zr). The mechanical property and corrosion performance of the studied two base alloys can be referenced to our previously published papers [22,23].

TIG welding was performed manually on Fronius welding machine parallel to the rolling direction of the alloy plates, using 3 mm newly developed Al–6.0Mg–0.25Sc–0.10Zr (wt%) welding wires, which can effectively reduce the risk for solidification hot cracking and improve the tensile property of fusion zone compared with conditional commercial filler materials, such as ER 5556, ER5183, ER5356, 5087, 5180 and 5093 [14]. Before TIG welding, the alloy plates were subjected to surface treatment. TIG welding parameters were: voltage 12–14 V, argon as shield gas (flow rate 12 L/min), current 95–102 A, and welding speed 100–120 mm/min. Friction stir welding was carried out in Beijing FSW Technology Co., Ltd. The welding direction was parallel to the rolling direction of plates. An FSW tool consists of a shoulder and a pin. The pin is in the shape of truncated cone and has a diameter of 2 mm, and the diameter of root shoulder is 10 mm. The tool rotation speed was 550–600 rpm and the travel speed of the tool was 200 mm/min.

The mechanical properties of all studied weld joints were evaluated by room temperature tensile tests, which were carried out at a cross-head speed of 2 mm/min, using transverse oriented tensile specimens (the long axis of tensile specimens was perpendicular to the welding direction or the rolling direction) with a gauge length of 70 mm and a width of 12 mm, designed according to the specification in IS0 4136 (2001): Destructive tests on welds in metallic materials. A minimum of five mechanical tests was performed on each sample, and their statistical scatter determined the measurement errors.

To characterize the microstructure and intermetallics distribution across the welded joints, a combined scanning electron microscopy (SEM), electron back scattered diffraction (EBSD), X-ray diffraction (XRD), optical microscopy (OM), energy disperse spectroscopy (EDS) and transmission electron microscopy (TEM) methods were applied.

To characterize intermetallics, SEM observations in back scattered electron imaging mode, combined with EDS analyses, were performed on a Quanta MK2-200 scanning electron microscope with energy disperse spectroscopy, operating at 20 kV. The fracture surfaces were investigated by SEM in secondary electron imaging mode. X-ray diffraction was carried out on a D/max 2500PC diffraction instrument with CuKα1 radiation. To examine the grain boundary characteristics in different microstructural zones in the welded joints, a Sirion 200 field emission gun scanning electron microscope equipped with EDAX TSL OIM v5 hardware and software was used to obtain and analyze electron back scattered diffraction data. In order to avoid spurious boundaries, a lower limit of 2° has been used in this investigation. Boundaries with misorientation angles between 2° and 15° were defined as low angle grain boundaries (LAGBs) and those with misorientation angles $>15°$ were defined as high angle grain boundaries (HAGBs). The black and red lines in EBSD maps indicate HAGBs and LAGBs, respectively, and the color of each grain is coded by its crystal orientation. Step sizes of 0.15–0.25 μm were used for the microstructural zones associated with lots of substructures, while larger step sizes were used for recrystallized microstructural zones in friction stir welded joint. All the step sizes were set to be much smaller than the grain sizes in corresponding microstructure zones. The samples used for OM observations were ground, polished and then etched by a solution of 2 ml HF, 3 ml HCl, 5 ml HNO_3 and 250 ml distilled water. To investigate the ageing precipitates, substructure and nano-particles, thin foils for transmission electron microscope observation were prepared by double-jet electro-polishing at 20 V in a solution of 30% nitric acid and 70% methanol solution cooled to -30 °C and observed on a TECNAI G^2 20 electron microscope, with an acceleration voltage of 200 kV.

3. Results

3.1. Microstructure of base metals

Fig. 1 shows the microstructure of Al–Zn–Mg and Al–Zn–Mg–Sc–Zr base alloys. The grain boundaries of Al–Zn–Mg alloy are mostly characterized by HAGBs, and the average grain size is determined to be about 12.6 μm (Fig. 1(a)). However, Al–Zn–Mg–Sc–Zr alloy still remains unrecrystallized deformed structure, which consists of about 2.0 μm subgrains with a high fraction of LAGBs (Fig. 1(b)). Very fine ageing phases in high density were distributed in the interior of grains in two studied alloys (Fig. 1(c) and (d)). According to the selected area diffraction pattern, the ageing