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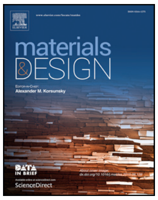

Investigation of microstructure evolution after post-weld heat treatment and cryogenic fracture toughness of the weld metal of AA2219 VPTIG joints

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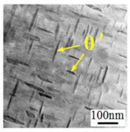
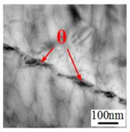
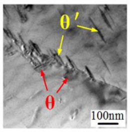
HIGHLIGHTS

- Aluminum alloy 2219 was welded by variable polarity tungsten inert gas arc welding.
- The effect of post-weld heat treatment on morphologies of precipitates was studied in detail.
- The cryogenic fracture toughness of the weld metal was investigated by crack tip opening displacement tests.
- The crack tip opening displacement values at 77 K were nearly 20% higher than those at 298 K.

GRAPHICAL ABSTRACT

Heat treatment conditon	**Base metal (T87)**	**As-welded weld metal**	**Post-weld heat treated weld metal**
Microstructure			
CTOD at 298K (mm)	**0.0719**	**0.1383**	**0.1294**
CTOD at 77K (mm)	**0.0903**	**0.1639**	**0.1548**

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ABSTRACT

In this work, the effect of post-weld heat treatment (solid solution + artificial aging) on the microstructure and cryogenic fracture toughness of the weld metal of VPTIG welded AA2219 joints were investigated by using crack tip opening displacement (CTOD) test method. The samples were divided into three types: (i) the weld metal of as-welded joint, marked as sample A; (ii) the weld metal of post-weld heat treated joint, marked as sample B; (iii) the base metal used for comparison, marked as BM. The results showed that the solution treatment dissolved θ phases, and the artificial aging treatment re-precipitated θ' phases. After post-weld heat treatment, the strength of weld metal was improved, accompanied with a little bit of decrease in the plasticity and fracture toughness. No matter what kind of sample types, compared to 298 K, the strength tested at 77 K was higher due to the weaker lattice vibration frequency and lower energy fluctuation. Besides, the plasticity was also higher at 77 K than that at 298 K, because the Peierls-Nabarro force was not sensitive to temperatures. Thus, the fracture toughness was also better at 77 K.

1. Introduction

High strength aluminum alloy 2219 (AA2219) has been widely used in aerospace field due to the excellent mechanical properties and weldability. And it has attracted interesting attention to be used as the material of large launch vehicle fuel storage tank [1–6].

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Tungsten inert gas (TIG) arc welding possessing many advantages, such as arc stability, good weld forming and pure metal composition, has been used to weld AA2219 [7–8]. However, using this method to weld AA2219 joints leads to a seriously decline of joint strength and only achieves 50–60% of the strength of base metal [9–10]. S. Malarvizhi and V. Balasubramanian et al. [10] improved the strength of TIG welding AA2219 joints by 10% using post-weld artificial aging treatment. Jikun Ding et al. [11–12] investigated the effect of post-weld "solid solution + artificial aging" treatment on properties of variable polarity TIG (VPTIG, an improved technique comparing to traditional TIG, which is able to output controllable current waveform and pulse current) welded AA2219 joints. It was found that, the improvement 43% for the strength of joints was achieved by this method. According to these previous studies, it is established that post-weld heat treatment could improve the strength of AA2219 joints.

Fracture toughness plays an important role in the structural integrity assessment of sheet metal, such as pressure vessels and tanks [13]. However, these studies failed to investigate the effect of the post-weld heat treatment on the fracture toughness. Furthermore, it is necessary for the rocket low-temperature storage tank to display an excellent cryogenic performance [14–15], which ask for a high stability of welded parts during employment in low temperature environments. It was known from our previous research that the weld metal was the weakest part of VPTIG welded AA2219 joints, and it associated to the performance of the whole welded tank [11–12,16]. In these cases, it is necessary, from a technological and economical point of view, to improve the low temperature performances (cryogenic strength and fracture toughness) of the weld metal.

The AA2219 joints were welded by VPTIG and the as-welded joints were treated with "solid solution + artificial aging". The cryogenic fracture toughness of weld metal was studied by using crack tip opening displacement (CTOD) test method. The influence of temperature and microstructures on the conventional mechanical properties and fracture toughness of weld metal were also discussed.

2. Experimental procedures

2.1. Welding and heat treatment process

AA2219-T8 plates, a thickness of 8 mm, were used as base metal. The chemical compositions were listed in Table 1. Butt welding was carried out using I-groove with no gap and there was no backing used. Before welding, the surface oxides were removed by grinding. The variable polarity TIG welding equipment (VPTIG, Dynasty 700, Miller, USA) was employed. The welded joints consisted of two passes (the root pass was welded without filling wire, under protection from high purity helium, while the cap pass was welded using ER2325 wire, under protection from high purity argon). The gas was continuously discharged from ceramic nozzle (cylindrical shape, d = 10 mm) connecting to the airway tube of the water-cooled torch. To keep the voltage stable, arc length controller (AVC-501, Jetline, USA) was used. In the whole process, a pulse modulation was superposed to the welding current to obtain a good weld appearance. The parameters of welding process are listed in Table 2.

According to the typical heat treatment specifications of AA2219 [5, 17], the specific post-weld heat treatment process was preformed following the steps below: First, solution treatment was conducted at 535 °C for a soaking time of 90 min with water quenching. Then, artificial aging treatment was carried out at 175 °C for a soaking time of 12 h with furnace cooling. Besides, the atmosphere box furnace (HMX1100-30A, Haoyue, China) was used to carry out heat treatment procedures. In this work, the samples were divided into three types: (i) the weld metal of as-welded joint, marked as sample A; (ii) the weld metal of post-weld heat treated joint, marked as sample B; (iii) the base metal used for comparison, marked as BM.

Table 1
Chemical compositions of AA2219 (wt%).

Si	Fe	Cu	Mn	Zn	V	Ti	Zr	Al
0.20	0.30	6.2	0.6	0.1	0.12	0.15	0.2	Bal.

Table 2
Welding parameters.

	Welding pass	Root	Cap
Variable polarity parameters	Average current (A)	270	255
	EN (A)	257	242
	EP (A)	324	305
	AC balance (%)	80	80
	AC frequency (Hz)	100	100
Pulse parameters	Pulse frequency (Hz)	2	2
	Peak pulse duration (%)	70	70
	Base pulse value/peak pulse value (%)	20	20
Voltage (V)		10–11	10–11
Welding speed (mm/s)		1.5	2.0
Wire feed speed (cm/min)		–	40
Gas flow (L/min)		15	15

2.2. Performance tests

The metallographic structure of welded joints was observed by optical microscope (OM, GX51, Olympus, Japan) and scanning electron microscope (SEM, S4800, Hitachi, Japan). In general, the cross-section of the joints was etched by Keller's reagent to better reveal the microstructure. The morphology of precipitates was analyzed by transmission electron microscopy (TEM, Tecnai G2 F20, FEI, USA). The thickness of samples was reduced by double injection electrolytic polishing with a methanol solution of 30% nitric acid as the etching solution.

The schematic diagram of the samples is shown in Fig. 1a. The sizes of the samples used for micro-mechanical tensile test were designed as that in Fig. 1c (cut from the location shown in Fig. 1a). The tensile test was conducted by using the micro-mechanical testing machine (AG250-KNIS, Shimadzu, Japan) at a loading rate of 1 mm/min. The test was conducted at 298 K and 77 K to collect the stress-strain curves, respectively. The tensile strengths, yield strengths and elongations obtained during the test were used as indicators to evaluate the tensile properties of joints.

According to the British standard BS7448 [18–19], the CTOD tests were conducted at both 298 K and 77 K. The three point bending (TPB) standard specimens with prefabricated fatigue crack were prepared and the size is shown in Fig. 1b. A notch is often machined in the center of the specimens, which acts as the initiation point of the fatigue crack. The specimen from BM is machined along the rolling direction and the specimen from weld metal is machined perpendicular to the welding direction (as shown in Fig. 1a). The fatigue cracks were performed using high-frequency fatigue testing machine (GPS20, China) in air at room temperature. Three point bending method was adopted as loading mode. The maximum compressive stress for BM, sample A and sample B was 1200 N, 500 N and 1000 N, respectively (stress ratio: 0.1). In this work, the fatigue crack length is 2 mm. The CTOD test was conducted using electronic universal testing machine (E45.105, MTS, USA), wherein the span is 56 mm and the loading rate is 1.0 mm/min. The force-displacement (P-V) curves were also obtained. The CTOD value is calculated from the following formula:

$$\delta = \left[\frac{FS}{BW^{1.5}} \times f\left(\frac{a_0}{W}\right)\right]^2 \times \frac{1-\mu^2}{2\sigma_{YS}E} + \frac{0.4(W-a_0)V_p}{0.4W+0.6a_0+z} \qquad (1)$$