



Effects of weld reinforcement on tensile behavior and mechanical properties of 2219-T87 aluminum alloy TIG welded joints

Guo-qing WANG¹, Quan LI², Yan-jun LI^{3,4}, Ai-ping WU^{3,4}, Nin-xu MA⁵, Dong-yang YAN¹, Hui-qiang WU¹

1. China Academy of Launch Vehicle Technology, Beijing 100076, China;

2. Capital Aerospace Machinery Company, Beijing 100076, China;

3. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China;

4. Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Tsinghua University, China;

5. Joining and Welding Research Institute, Osaka University, Osaka, Ibaraki 567-0047, Japan

Received 23 May 2016; accepted 29 November 2016

Abstract: Tungsten inert gas (TIG) welded joints for 2219-T87 aluminum alloy are often used in the fuel tanks of large launch vehicles. Because of the massive loads these vehicles carry, dealing with weld reinforcement on TIG joints represents an important issue in their manufacturing and strength evaluation. Experimental and numerical simulation methods were used to investigate the effects of weld toe shape and weld toe position on the tensile behavior and mechanical properties of these joints. The simulation results indicated that the relative difference in elongation could be as large as 96.9% caused by the difference in weld toe shape. The joints with weld toes located in the weld metal or in the partially melted zone (PMZ) exhibited larger elongation than joints with weld toes located at the juncture of the weld metal and the PMZ.

Key words: tensile strength; weld reinforcement; 2219-T87 aluminum alloy; TIG welding; digital image correlation (DIC) technique

1 Introduction

2219 alloy is an Al–Cu–Mn ternary alloy with excellent cryogenic properties, high fracture toughness, and stress corrosion resistance. It is often used in manufacturing fuel tanks for large launch vehicles, such as the Thor and Delta rockets, Saturn V, and the space shuttles [1–3]. Under T8 heat treatment, it has excellent stress corrosion cracking resistance and can be applied as covering for supersonic aircraft [4].

Variable polarity tungsten inert gas (VPTIG) arc welding is an appropriate process for welding aluminum alloys, and it has wide applications in various industries, especially aviation and aerospace [5]. In 2219-T87 VPTIG joint, the weld metal generally has less hardness and strength than other parts of the joint due to its solidification microstructure. In practical welding structures, the strength shortage in the weld metal is often offset by weld reinforcement. However, the weld reinforcement can induce stress concentration around the weld toe, impairing its reinforcing effects. Furthermore,

a partially melted zone (PMZ) exists adjacent to the weld [6–9], in which there is near-continuous θ phase along the α (Al) grain boundary that causes serious deterioration of the PMZ's plasticity. In addition to these two regions of weakness, an over-aged zone (OAZ) exists in 2219-T87 VPTIG joints because of the effects of the thermal welding cycle, and the most serious OAZ (the hardness of which is the lowest in the heat affected zone) lies close to the PMZ. Consequently, the 2219-T87 VPTIG joint consists of different zones with different mechanical properties and geometric shapes. In other words, the joint is heterogeneous in both properties and geometry, such that the joint's tensile behavior becomes very complicated. NASA researchers investigated the geometrical and microstructural effects on tensile behavior of 2219 aluminum alloy fusion welded joints [10,11]. However, insufficient research has been conducted on the effects of the weld reinforcement's shape on the welded joint's tensile behavior.

In this work, the effects of the geometry of the weld reinforcement on the tensile behavior and properties of the joint were investigated through experimental

methods and numerical simulation. Various tensile tests were conducted on joints with reinforcement on two sides, reinforcement on one side, and no weld reinforcement, in order to investigate the tensile properties of different joints. During the tensile tests, the strain distributions on the joints were measured using the digital image correlation (DIC) technique in order to acquire the constitutive properties of different joints' zones. The tensile behaviors of joints with different kinds of weld reinforcement were computed using finite element method (FEM). The effects on the joint's tensile behavior of the position of the weld toe and the weld reinforcement's shape, especially the transition between the weld reinforcement and the plate surface, were examined in detail. The results of this work could provide constructive suggestions for controlling the weld reinforcement shape and the position of the weld toe in practical structures.

2 Experimental

As a base material, this experiment used 2219 aluminum alloy plate with T87 heat treatment and 6.0 mm in thickness. The butt joint was created with a two-layer weld on one side. The first layer experienced direct current helium arc welding without a groove and filler metal. The second layer underwent VPTIG arc welding with ER2319 as a filler metal. The welding parameters are listed in Table 1.

Table 1 Welding parameters for double-pass TIG welding of 2219-T87 aluminum alloy

Pass	Current/A	Voltage/V	Speed/(mm·s ⁻¹)
First	185	19	4.3
Second	Peak: 305–315	Peak: 22–23	2.3
	Base: 160	Base: 17	

Pass	Shielding gas	Flow rate/(L·min ⁻¹)	Filler wire	Pulse-on ratio
First	He	10	—	—
Second	Ar	11–12	2325	0.63

A transverse tensile test was conducted on the joint according to the standard procedure (GB/T 228.1–2010) with a crosshead speed of 2 mm/min. The dimensions of the tensile sample are shown in Fig. 1. The gauge length was 50 mm.

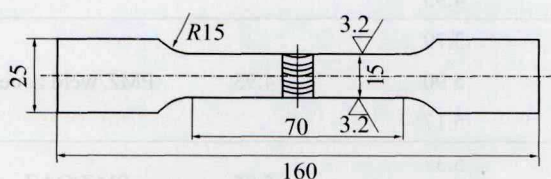


Fig. 1 Dimensions of tensile specimen (unit: mm)

DIC, a non-contact method of strain measurement, was frequently used to determine the local constitutive properties of heterogeneous materials, especially welded joints [12–14]. This work used an Aramis 4M optical measuring system developed by GOM mbH as a DIC device to measure the constitutive properties of different regions in the joints.

3 Simulation model

A numerical simulation of the joint's tensile behavior was conducted using ABAQUS finite element software. With the micro-hardness testing results, the joint was divided into different regions, including the weld zone, the PMZ, the OAZ, and the base material. This method of numerical simulation is commonly used to study the global mechanical properties of welded joints [15,16]. The geometric model of the joint with the element division is shown in Fig. 2. The material parameters of various regions in the 2219-T87 TIG joint (listed in Table 2) were determined based on the DIC results, according to a detailed method described by LI et al [17]. Using the fracture strain criterion, the tensile fracture behavior of the joint was analyzed. When the equivalent plastic strain of the integral point reached its fracture strain, the corresponding element failed, initiating the fracture.

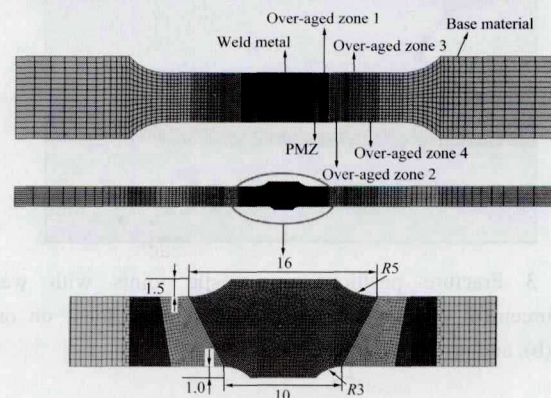


Fig. 2 Numerical simulation model of joint with weld reinforcement on both sides (unit: mm)

Table 2 Material parameters of various regions in joint

Region	Elastic limit stress/MPa	Hardening exponent	Fracturing strain	Maximum stress/MPa
Weld zone	70	0.31	0.22	312
PMZ	110	0.30	0.14	381
OAZ 1	90	0.31	0.32	375
OAZ 2	155	0.26	0.31	435
OAZ 3	220	0.21	0.31	475
OAZ 4	285	0.16	0.31	523
Base material	349	0.11	0.31	538

Stress and strain are true stress and true strain, respectively

4 Results

Figure 3 shows the fracture positions of these three joints, with no weld reinforcement, weld reinforcement on two sides, and weld reinforcement on one side. And Table 3 displays the measured tensile properties of these three types of joint. The joint with two-sided weld reinforcement had the highest strength and lower elongation. The fracture occurred between the PMZ and the weld zone. The elongations of these three specimens varied from 3.79% to 5.90%. When the back reinforcement was shaved, the joint had medium strength and the highest elongation, and the fracture initiated at the PMZ. The joint without reinforcement had the lowest strength and lower elongation, and the fracture started from the weld.

These results indicate that weld reinforcement exerts notable effects on the tensile properties of the joints. Moreover, the difference in the tensile properties

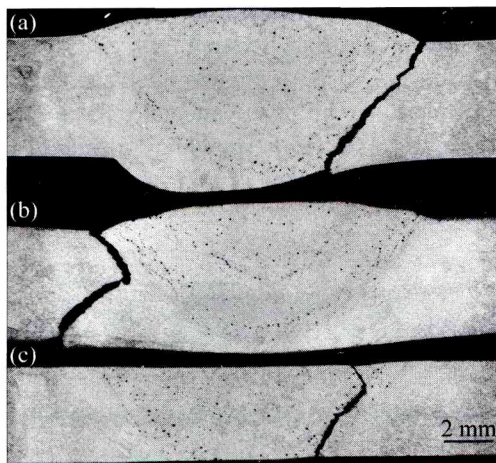


Fig. 3 Fracture positions on tensile joints with weld reinforcement on two sides (a), weld reinforcement on one side (b), and no weld reinforcement (c)

among the joints with weld reinforcement on two sides demonstrates that the weld reinforcement's shape or transition mode may influence the tensile properties of the joints.

5 Predicting effects of weld reinforcement

According to the weld shape measuring results, the height of the weld reinforcement remained nearly constant, while the weld toe shape was quite different. In some of the joints, the surface transitioned directly from the plate to the weld. We called this mode as the direct transition mode with angle θ . In other joints, the surface transitioned into featured curvature. We called this mode as the curve transition mode with radius r . The shapes of the weld reinforcements can be classified into four simple types, as shown in Fig. 4. In the simulation model, the shape at the weld toes was described by two parameters, radius r and angle θ . In this work, the effects of the weld reinforcement's transition mode as described by θ and r on the joint's strain distribution, nominal stress, and elongation at crack initiation were investigated.

Furthermore, the optical microstructure revealed that the joints' weld toe positions were also different. The weld toe may be located at the juncture of the weld and the PMZ or at the PMZ. The effects of the weld toe position on the tensile behavior of the joint were also analyzed through the numerical simulation method.

5.1 Joints with RR -shape and $R\theta$ -shape weld reinforcements

We investigated the tensile behavior of joints with different back reinforcement transition modes, given that the weld reinforcement of the front side transitioned with a $R5$ mm curve. Figure 5 shows the equivalent plastic strain distributions on the central cross-section of the joints at the moment of crack initiation (first element

Table 3 Tensile properties of base materials and three kinds of joints

Specimen	No.	Maximum tensile strength, σ_b /MPa	Average σ_b /MPa	Elongation after fracture, δ /%	Average δ /%	Fractured position
Base material	T0-4	451.7	452.4	12.60	13.00	
	T0-5	453.0		13.40		
No weld reinforcement	T2-1	254.7	255.0	4.68	4.98	Weld zone
	T2-2	258.0		5.31		
	T2-3	252.3		4.95		
Weld reinforcement on two sides	T2-4	274.8	282.7	3.79	4.95	PMZ/weld zone
	T2-5	288.0		5.90		
	T2-6	285.2		5.17		
Weld reinforcement on one side	T2-7	273.1	272.4	5.37	5.85	PMZ/OAZ
	T2-9	271.6		6.33		

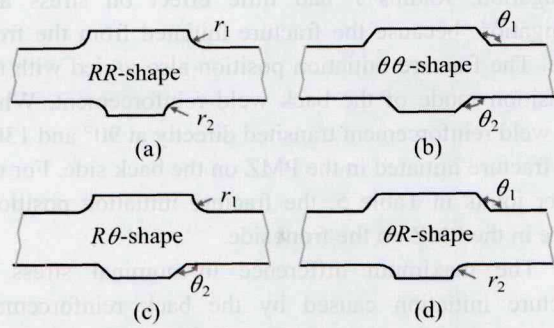


Fig. 4 Shapes of weld reinforcements: (a) RR -shape; (b) $\theta\theta$ -shape; (c) $R\theta$ -shape; (d) θR -shape

failure). The relevant load, nominal stress, and elongation at fracture initiation are listed in Table 4.

Plastic strain was concentrated around the weld toes (see Fig. 5). The deformation of the weld was higher

than in other regions of the joints, and it was affected by the transition mode of the back weld reinforcement. The deformation of the weld was the smallest when the back reinforcement transitioned with $\theta=90^\circ$ (Fig. 5(a)). In contrast, when the back reinforcement transitioned with $r=4.5$ mm, the deformation of the weld was at a maximum (Fig. 5(d)). These results can be explained as follows. The concentrated stress around the weld toe was triaxial. The stress triaxiality and concentration in the back weld toe transitioned with $\theta=90^\circ$ were higher than those transitioned with $r=4.5$ mm. The fracture strain always decreased with the increase of the triaxiality. Thus, the joint in Fig. 5(a) fractured early before the weld getting enough deformation.

For different joints, the strain concentrations and weld deformations were different, meaning that nominal stress and joint elongation were also different. The nominal stress and elongation of joints with $R\theta$ -shape

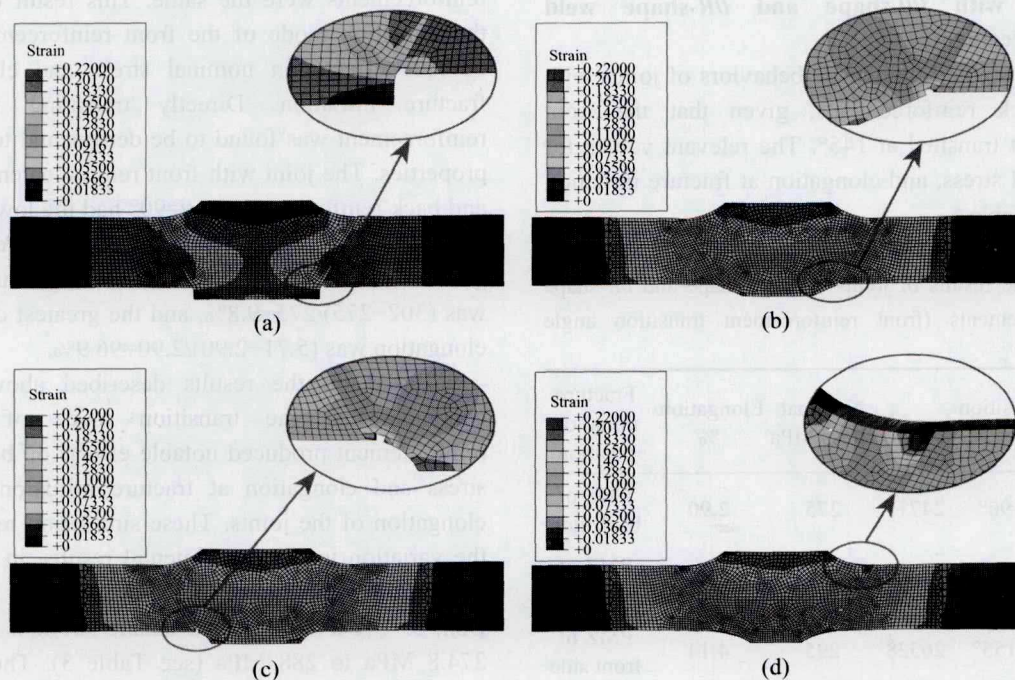


Fig. 5 Equivalent plastic strain distributions on central cross-section of joints at fracture initiation with direct (a, b) or curve (c, d) transition of back weld reinforcement (front reinforcement transition radius $r=5$ mm): (a) $\theta=90^\circ$; (b) $\theta=155^\circ$; (c) $r=1.5$ mm; (d) $r=4.5$ mm

Table 4 Tensile results of joints with $R\theta$ -shape and RR -shape weld reinforcement (front reinforcement transition radius $r=5$ mm)

Back side transition mode	Transition parameter	Load/N	Nominal stress/MPa	Elongation/%	Fracture initiation position
Direct	$\theta=90^\circ$	24747	275	3.09	PMZ of back side
	$\theta=130^\circ$	25809	287	3.81	PMZ of back side
	$\theta=155^\circ$	26716	297	4.70	Weld of back side
Curved	$r=1.5$ mm	26774	297	4.84	Weld of back side
	$r=3.0$ mm	27032	300	5.36	Weld of back side
	$r=4.5$ mm	27154	302	5.71	Weld of front side

Load, nominal stress, and elongation value correspond to crack initiation

weld reinforcement were lower than those with the RR -shape, and the values decreased with decreasing θ . For joints with RR -shape weld reinforcements, smaller r values produced less nominal stress and elongation. The fracture initiation position also varied with the transition mode of the back weld reinforcement. When the weld reinforcement transitioned directly at 90° and 130° , the fracture initiation position was located in the PMZ on the back side. When the weld reinforcement transitioned with curvature of 4.5 mm in radius, the fracture initiated in the weld metal on the front side. The other joints fractured in the weld metal on the backside.

The greatest difference in nominal stress at fracture initiation caused by the back reinforcement transition modes was $(302-275)/275=9.8\%$, and the greatest difference in elongation was $(5.71-3.09)/3.09=84.8\%$.

5.2 Joints with $\theta\theta$ -shape and θR -shape weld reinforcements

We also studied the tensile behaviors of joints with different back reinforcements, given that the front reinforcement transitioned at 145° . The relevant values for load, nominal stress, and elongation at fracture initiation are listed in Table 5.

Table 5 Tensile results of joints with $\theta\theta$ -shape and θR -shape weld reinforcements (front reinforcement transition angle $\theta=145^\circ$)

Back side transition mode	Transition parameter	Load/N	Nominal stress/MPa	Elongation/%	Fracture initiation position
Direct	$\theta=90^\circ$	24711	275	2.90	PMZ of back side
	$\theta=130^\circ$	25660	285	3.44	PMZ of back side
	$\theta=155^\circ$	26528	295	4.14	PMZ of front side
Curved	$r=1.5\text{mm}$	26575	295	4.24	PMZ of front side
	$r=3.0\text{mm}$	26245	292	4.04	PMZ of front side
	$r=4.5\text{mm}$	26287	292	4.16	PMZ of front side

Load, nominal stress, and elongation values correspond to crack initiation

The transition mode of the back weld reinforcement also produced notable effects on load and elongation. Joints with directly-transitioning back reinforcement had lower nominal stress and elongation, especially when θ was 90° and 130° . Stress and elongation decreased with decreasing θ . Joints with curved back reinforcement transitions had higher values for nominal stress and

elongation. Radius r had little effect on stress and elongation, because the fracture initiated from the front side. The fracture initiation position also varied with the transition mode of the back weld reinforcement. When the weld reinforcement transitioned directly at 90° and 130° , the fracture initiated in the PMZ on the back side. For the other joints in Table 5, the fracture initiation positions were in the PMZ on the front side.

The maximum difference in nominal stress at fracture initiation caused by the back reinforcement transition modes was $(295-275)/275=7.3\%$, and the maximum difference in elongation was $(4.24-2.90)/2.90=46.2\%$.

A comparison of the tensile results of joints with curved transitioning ($r=5\text{ mm}$) front reinforcements and direct transitioning ($\theta=145^\circ$) front reinforcements revealed that the former group had higher values for nominal stress and elongation when the back reinforcements were the same. This result implied that the transition mode of the front reinforcement exerted obvious effects on nominal stress and elongation at fracture initiation. Directly transitioning front weld reinforcement was found to be detrimental to the tensile properties. The joint with front reinforcement of $\theta=145^\circ$ and back reinforcement of $\theta=90^\circ$ had the lowest nominal stress and elongation. Within the 12 computed cases, the greatest difference in nominal stress at fracture initiation was $(302-275)/275=9.8\%$, and the greatest difference in elongation was $(5.71-2.90)/2.90=96.9\%$.

Based on the results described above, we can conclude that the transition mode of the weld reinforcement produced notable effects on both nominal stress and elongation at fracture initiation, especially elongation of the joints. These simulation results reflect the variation in the experimental results, in which joint elongation with weld reinforcement on two sides varied from 3.77% to 5.90%, and tensile strength varied from 274.8 MPa to 288 MPa (see Table 3). The joint with two-sided directly transitioning weld reinforcement had the lowest nominal stress and elongation, while the joint with curved transitioning weld reinforcement had higher nominal stress and elongation. The smaller the value of θ or r was, the lower the stress and elongation were. When the weld reinforcement transition angle θ on one side of the joint was smaller than 155° , the fracture initiated from the PMZ around the weld toe. When the two-sided weld reinforcement transitioned with a curve, the fracture initiated from the weld metal around the weld toe. The fracture of the joint is related with the stress concentration and the materials' mechanical properties around the weld toe. The influence mechanism of the weld toe shape on the fracture behavior of the joint needs further research.

5.3 Effects of weld toe position

We calculated the tensile behavior of different joints, in which the front weld toe position varied among the weld, juncture, and PMZ (Fig. 6) while the front weld reinforcement transitioned with θ value of 145° . The nominal stress and elongation at fracture initiation are given in Table 6. The data demonstrated that when the back weld reinforcement transitioned with a radius of 4.5 mm, the fracture initiated from the front side. The weld toe position on the front side had some effect on nominal stress and a stronger effect on elongation. The joints with the weld toe located in the weld metal or in the PMZ had greater elongation than joints with the weld toe located at the juncture of the weld metal and the PMZ.

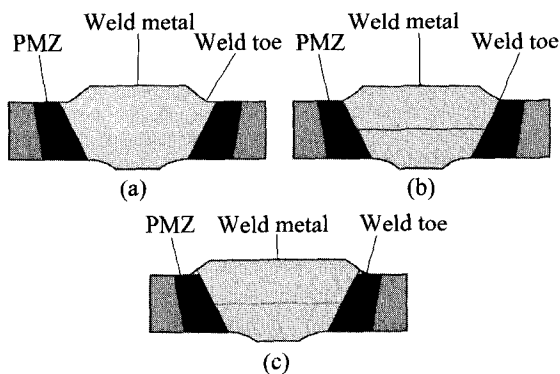


Fig. 6 Schematic diagrams of joints with weld toes located in weld metal (a), at juncture of weld metal and PMZ (b), and in PMZ (c)

Table 6 Effects of front weld toe position (front weld reinforcement transition at 145°)

Back side transition mode	Front side weld toe position	Load/N	Nominal stress/MPa	Elongation/%	Fracture initiation position
Curved at 4.5 mm	WM	26245	291.6	4.51	Weld of front side
	Juncture	26287	292	4.16	PMZ of front side
	PMZ	27364	304.0	4.85	PMZ of front side
Direct at 90°	WM	24802	275.6	3.10	PMZ of back side
	Juncture	24711	275	2.90	PMZ of back side
	PMZ	24905	276.7	2.88	PMZ of back side

Load, nominal stress, and elongation values correspond to crack initiation

When the back weld reinforcement transitioned at an angle of 90° , the position of the front weld toe had little effect on the nominal stress and elongation because the fracture initiated from the PMZ on the back side. These

results indicated that the position of the weld toe had some effects on the nominal stress and an even stronger effect on the elongation when the fracture initiated from the same side. Joints with weld toes located in the weld metal or in the PMZ exhibited greater elongation than joints with weld toes located at the juncture of the weld metal and the PMZ.

6 Conclusions

1) The results of these experiments and simulations indicated that the transition mode of the weld reinforcement exerted notable effects on the tensile strength and elongation of the joint, as well as the nominal stress and elongation of the joint at fracture initiation, with elongation experiencing especially strong effects. The greatest relative difference in elongation was 46.2% according to the experiment results and 96.9% according to the simulations.

2) The joint with two-sided directly transiting weld reinforcement had the lowest nominal stress and elongation, while the joint with curved transitioning weld reinforcement had higher nominal stress and elongation. The smaller the value of θ or r was, the lower the stress and elongation were.

3) The position of the weld toe had some effects on nominal stress and elongation at fracture initiation when the fracture initiated from the same side. Joints with weld toes located in the weld metal or in the PMZ exhibited greater elongation than joints with weld toes located at the juncture of the weld metal and the PMZ.

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焊缝余高对 2219-T87 铝合金 TIG 焊接头拉伸行为及力学性能的影响

王国庆¹, 李 权², 李艳军^{3,4}, 吴爱萍^{3,4}, 麻宁绪⁵, 鄢东洋¹, 吴会强¹

1. 中国运载火箭技术研究院, 北京 100076;

2. 首都航天机械公司, 北京 100076;

3. 清华大学 机械工程系, 北京 100084;

4. 清华大学 先进成形制造教育部重点实验室, 北京 100084;

5. Joining and Welding Research Institute, Osaka University, Osaka, Ibaraki 567-0047, Japan

摘 要: 运载火箭燃料贮箱通常采用 2219-T87 铝合金钨极氩弧焊(TIG)生产。由于贮箱服役时的承载环境比较严苛, TIG 焊接头的余高控制是贮箱生产及其性能评价中的重要问题。采用实验和数值模拟的方法研究焊趾形状和焊趾位置对接头拉伸行为及力学性能的影响。研究表明, 焊趾形状对接头的伸长率影响显著, 数值计算的结果中伸长率最低值与最高值相差达 96.9%; 启裂侧焊趾处于焊缝和部分熔化区时接头伸长率高于焊趾处于焊缝与部分熔化区交界处的。

关键词: 拉伸强度; 焊缝余高; 2219-T87 铝合金; TIG 焊; 数字图像相关(DIC)技术

(Edited by Xiang-qun LI)