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Friction stir welding of high-strength aerospace aluminum aAlloy and application in rocket tank manufacturing

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ABSTRACT

Friction stir welding (FSW) has been widely adopted in aerospace industry for fabricating high-strength aluminum alloy structures, such as large volume fuel tanks, due to its exceptional advantages including low distortion, less defects and high mechanical properties of the joint. This article systematically reviews the key technical issues in producing large capacity aluminum alloy fuel tanks by using FSW, including tool design, FSW process optimization, nondestructive testing (NDT) techniques and defect repairing techniques, etc. To fulfill the requirements of Chinese aerospace industry, constant-force FSW, retractable tool FSW, lock joint FSW, on-line NDT and solid-state equal-strength FSW techniques, as well as a complete set of aerospace aluminum FSW equipment, have been successfully developed. All these techniques have been engineered and validated in rocket tanks, which enormously improved the fabrication ability of Chinese aerospace industry.

1. Introduction

High-strength aluminum alloys have been increasingly employed in welding of large aerospace structures, such as fuel tanks of launch vehicle, space shuttles and space ships. The welded structures usually experience a complex internal/external pressure and structure torque during the service which requires the high-standard welds. With the advancement of manned spacecraft and deep space exploration projects, however, conventional fusion welding technique is no longer competitive to fulfill the requirement of rocket fuel tanks with high reliability and high efficiency production.

Friction Stir Welding (FSW) is a solid-state joining process invented in 1991 by The Welding Institute (TWI) in the UK. As soon as the technique was invented, it drew extensive interests from aerospace industry owing to its exceptional advantages including less defects, low distortion and excellent joint performance [1]. FSW has been accepted as an ideal technique for joining large aerospace structure made of high-strength aluminum alloys.

The first friction stir welded unclosed inter-tank section was produced by Boeing of the United States for Delta II launch vehicle and passed the flying tests in October 1999. Then, FSW was adopted in producing Delta IV launch vehicle which approved by space mission in April 2004 [2,3]. More and more engineering practices and successes in space vehicles, such as space shuttle series, Ares I launch vehicle, Orion spacecraft and Space Launch System (SLS), and other pressurized tanks of spacecrafts paved the way to eventually substitute FSW for conventional fusion welding [4–10]. Apart from the U.S., Japan took active role in the aerospace industry for adopting FSW technique and successfully launched H2B rocket with FSW joints in September 2009 [11].

China's interest in FSW has been growing since the late 20th century. Focused on high-strength aluminum aerospace structures, extensive research and development were carried out and significant successes were achieved [12–15]. This article will firstly introduce the FSW development of high strength aerospace aluminum alloys in China, and then discuss the successes of applying FSW in welding large thin-wall low-rigidity fuel tanks. In addition, on the basis of the current technical achievement and future strategic plan, a technical roadmap for applying FSW in aerospace industry is proposed.

2. Friction stir welding of high-strength aluminum aerospace structure

AA2219 alloy, as a replacement of AA2014, is widely used as a main material in launch vehicles and spaceships as it is characterized by low density, high specific strength and specific modulus. However, by use of conventional fusion welding, the porosities and hot cracking are commonly found in the joined structures

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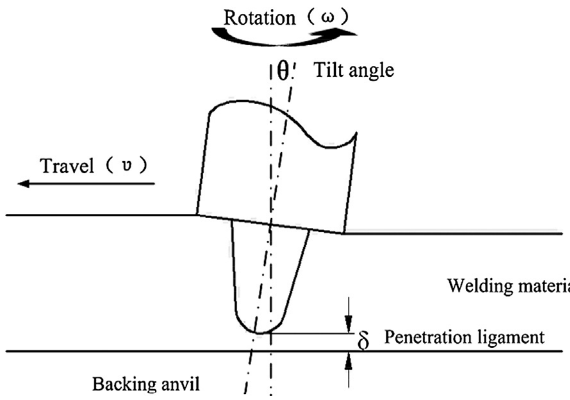

Fig. 1. FSW process with tilt angle tool [12].

of the alloy. Since FSW has been proven to be an ideal candidate to replace conventional fusion welding in producing large high-strength Al fuel tanks, AA2219 was developed. The core technologies on AA2219 FSW, in terms of tool geometry, process control, NDT and weld repair, were investigated, which laid the foundation for the application of FSW on new model of launch vehicle.

2.1. Development of FSW tool

The development of FSW tool is an indispensable part in research of FSW. During the FSW process, the tool profile directly determines the heat generation and plastic flow of material under the complicated heat-force action and therefore has significant impact on mechanical properties and defect formation of FSW joints. The development on this respect passed through three stages:

(1) Concave shoulder tool

As a commonly used type of tool, the concave shoulder tool is usually operated with a tilt angle of $2^{\circ}-3^{\circ}$ and designed with inward angle at $7^{\circ}-12^{\circ}$ and a concave profile on the shoulder which form inward and downward forces on the plasticized metal of weld face (Fig. 1). In later application, especially in welding of high-strength aluminum alloys and thick plates, the concave shoulder was reformed to enhance the welding heat input and interior metal flow. The pin geometry was evolved as well from single Screw Thread to present Three Flats and MX-Triflute^{TM} (Fig. 2). The diameter ratio of conventional tool shoulder and pin root was also taken into account. Although at $2.5^{\circ}-3^{\circ}$ as usual, the thicker of workpiece is, the lower the ratio needs to be. Despite of its wide application in rocket fabrication, however, problems of this type of tool were encountered, for examples, welding with tilt angle led to thinning on the weld face to some extend and it was difficult to weld complex path and 3-dimensional curved joints.

(2) Plane shoulder tool with Archimedean spiral

This type of tool is operated without angle tilting and suitable for longitudinal straight joint (Fig. 3). The inward Archimedean spiral profile helps excellent formation of joint and hardly causes the thinning of the weld. However, the process has to be adjusted frequently due to the poor adaptability to the plunge depth of the shoulder. Moreover, the need for high assembly accuracy hinders the wider application in fuel tank welding.

(3) Convex or cone/convex sphere shoulder tool with Archimedean spiral

Due to the high adaptability to the plunge depth of the shoulder, this type of tool (Fig. 4) are employed for welding both with tilting angle of $0.5^{\circ}-1^{\circ}$ or without any angle and usually achieve

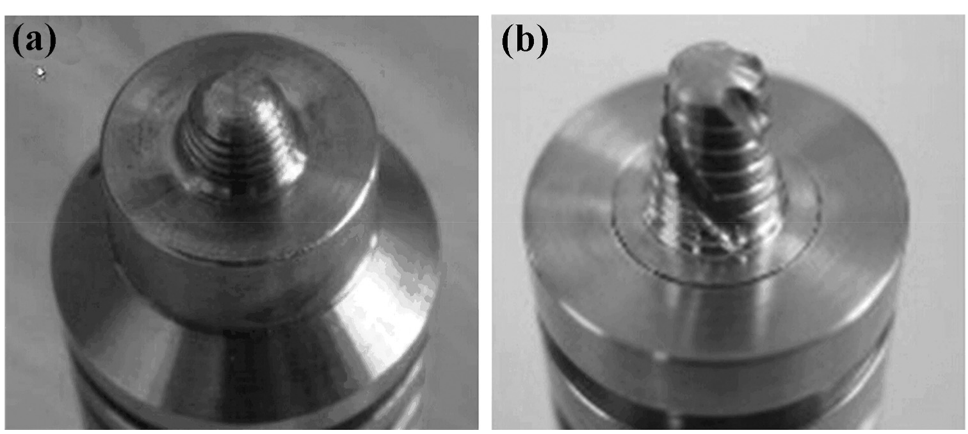

Fig. 2. The first generation of FSW tool: (a) Concave shoulder plus Threads pin, (b) Concave shoulder plus Threads & Flutes pin.

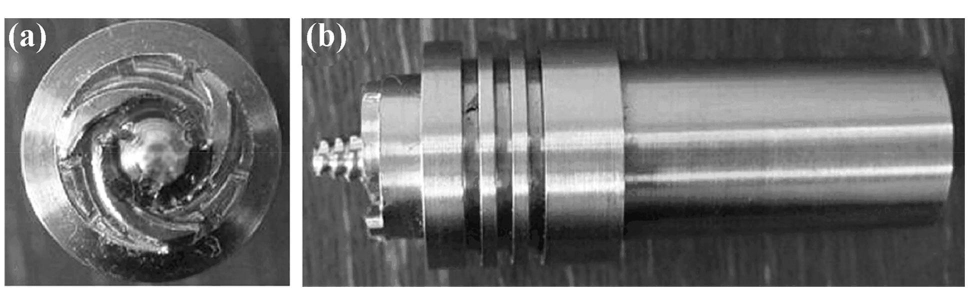

Fig. 3. The second generation of FSW tool with plane shoulder plus Archimedean spiral: (a) top view, (b) main view.

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