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New technique for eliminating keyhole by active-passive filling friction stir repairing

Shude Ji *, Xiangchen Meng, Yaming Zeng, Lin Ma, Shuangsheng Gao

Faculty of Aerospace Engineering, Shenyang Aerospace University, No.37 Daoyi South Avenue, Daoyi Development District, Shenyang 110136, China

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ABSTRACT

In order to eliminate the volume defects such as keyhole and cavity in friction stir welding (FSW) joint, a new technique called active-passive filling friction stir repairing (A-PFFSR) was put forward. In this study, choosing AZ31-B magnesium alloy as research object, repairing experiment of keyhole was mainly investigated. The results show that the keyhole can be successfully repaired and no defects appear in filling zone (FZ) of joint using the plunge speed of 1 mm/min and rotational velocity of 1300 rpm. The FZ and partial thermo-mechanically affected zone are characterized by fine and equiaxed grains, while the grain size of FZ through the thickness direction presents bigger in the middle and smaller in the top and bottom of joint. With the increase of plunge speed, tensile strength and elongation of repaired joints gradually decrease at the constant rotational velocity of 1300 rpm. When the plunge speed is 1 mm/min, the tensile strength and elongation of A-PFFSR joint reach the maximum values of 189.7 MPa and 7.6%, equivalent to 96.3% and 98% of defect-free FSW joint, respectively. Moreover, the fracture surface consists of dimples with varied size, indicating typical ductile fracture.

1. Introduction

Recently, with the demand of energy-saving and emission-reduction, magnesium alloy has been widely used to transportation and electronic industries because of the advantages of low density, high specific strength and good damp capacities [1,2]. Therefore, the welding technique of magnesium alloy has attracted more and more attentions at home and abroad. When using fusion welding technique, the defects such as porosity, crack and lack of fusion inevitably appear in the joint, which always degrade mechanical property of welding joint [1,3].

As a solid state welding technique, friction stir welding (FSW) has the advantages of high joint strength, low distortion, no cracks, low power consumption and non-pollution. Therefore, FSW has extensively been used in automotive, aerospace, electronics and shipbuilding [4–6]. During welding process, a non-consumable rotational tool with high rotational velocity is plunged into workpieces and moves along the welding line, finishing welding process. However, welding defects such as cavity, kissing bond and tunnel easily form under improper process parameters or technological conditions [7–10]. Therefore, some researchers at home and abroad have put forward some methods to solve the disadvantages induced by these defects. Liu et al. [10] used re-FSW method to eliminate groove defect and found that proper offset was beneficial to enhance joint quality. Ji et al. [11] proposed vertical compensation friction stir welding (VCFSW) to eliminate groove, tunnel and gap defects and then obtained high quality joint. Besides the above-mentioned defects, the most typical feature of macroscopic morphology of FSW joint is keyhole defect, which results from retraction of rotational pin at the final stage of welding [12–20]. Normally, the keyhole owns the weakest joining effect due to small joining area. Therefore, the repairing technique of keyhole defect has become research hotspot. Up to present, quite a few methods and apparatuses have been put forward [12–21].

In order to avoid the keyhole, an auto-adjusting pin tool invented by National Aeronautics and Space Administration can incrementally withdraw at the final welding stage [12]. Similar to auto-adjusting pin tool, the retractable [13] or double acting re-filling tool [14] consisting of a detached shoulder and pin has also been proposed to avoid the keyhole by controlling the relative movement between shoulder and pin. Although the above-mentioned apparatuses can effectively avoid the keyhole, these welding tools are installed complicatedly and expensively, which goes against the development of FSW.

Based on the characteristic of solid state joining, friction taper plug welding (FTPW), friction bit joining (FBJ) and filling friction stir welding (FFSW) processes using special designed and consumable tool have also been proposed by TWI [15,16], Miles et al. [17] and Huang et al. [18,19], respectively. During FTPW process, a tapered plug is friction welded to the hole with included angle in a few seconds by forcing the rotating plug. It can be used in several applications, for example, at the location of crack defect in offshore steel and aerospace aluminum structures that are intended to be repaired [15,16]. The FBJ process was initially developed to spot joining, in which a consumable bit is considered as filler material and frictions with workpieces, finishing joining process. During FFSW process, a semi-consumable tool is employed to eliminate keyhole defect. The results showed that the tensile strength of FFSW

* Corresponding author.
E-mail address: superjsd@163.com (S. Ji).

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Table 1
Nominal chemical compositions and mechanical properties of BM.

Material	Nominal chemical composition (wt.%)							Mechanical properties		
	Al	Si	Fe	Cu	Mn	Zn	Mg	UTS (MPa)	EL (%)	MH ($HV_{0.1}$)
AZ31-B	3.05	0.016	0.001	0.003	0.44	1.10	Bal.	240	12	58

Table 2
Feature, diameter and effective filling depth of rotational tool used in this experiment.

Process	Procedure	Tool geometry	Shoulder diameter(mm)	Plunge depth(mm)	Filling depth(mm)
A-PFFSR	AF-1	Pinless tool	6 mm	3.0 mm	1.0 mm
	AF-2	Pinless tool	10 mm	1.5 mm	1.5 mm
	PF	Pinless tool + filler material	14 mm	0.1 mm	1.4 mm

joint reached 174.7 MPa, equivalent to 95% of FSW joint. However, owing to insufficient frictional heat and material flow at the bottom of keyhole, the voids easily forms in the interface between filling bit and keyhole, which is detrimental to mechanical properties [18,19]. The consumable bit always needs to be special design and manufacturing, increasing procedures [15–17].

Aiming at thin-wall construction, Luan et al. [20] put forward friction flow welding (FFW) to repair the keyhole of FSW of 6082-T6 aluminum alloy, in which a rob material as same as BM and pinless tool with helical structure were used. The results indicated that the FFW could successfully repair the keyhole whose depth is lower than 2.5 mm. However, the keyhole with bigger depth is difficult to repair owing to insufficient material flow [20].

Not only that, Zhou et al. [21] also put forward a repairing method named self-refilling friction stir welding(SRFSW) to fill keyhole with the depth of 5 mm, which depends on a series of rotational tools owning gradual change in geometry. The results exhibited that the refilled joint of 316 stainless steel fractured at BM, and the tensile strength and elongation reach 112% and 82% of BM, respectively. However, the keyhole was only self-refilled without filler metal, which often results in thickness reduction of workpiece, deteriorating mechanical performance.

Therefore, in order to eliminate the keyhole with bigger depth and then obtain high quality repaired joint, a new technique named active-passive filling friction stir repairing (A-PFFSR) was proposed by employing a series of non-consumable pinless tools and an extra filler material. In this study, 4 mm thick AZ31-B magnesium alloy plate is chosen as research object, which owns worse plastic deformability owing to the limitation of number of slip systems of hexagonal close packed (HCP) crystal lattice [22,23]. Meanwhile, surface formation, microstructure and mechanical properties of repaired joint are further investigated in details.

2. Experimental

The base material (BM) used in this study was AZ31-B magnesium alloy plate, whose dimensions are 300 mm × 100 mm × 4 mm. The chemical composition and mechanical properties of BM are shown in Table 1. In this study, the A-PFFSR process is divided into two parts: one is active filling (AF), the other is passive filling (PF). The schematic diagram of A-PFFSR is indicated in Fig. 1. The keyhole can be repaired using different pinless rotational tools with different diameters step by step. The keyhole in AF process is filled with materials surrounding keyhole. Extra filler material in PF process is the same as BM. The diameter of extra filler material is the same as that of rotational tool used in last step and the height is higher than depth of unfilled keyhole. During the two processes, the filler material is heated and plasticized by frictional heat generated by pinless tool. Under the stirring effect of rotational tool, sufficient material flow behavior can be produced, which results in effective filling of keyhole. In addition, the forging force provided by rotational tool is beneficial to solid state bonding between two filling layers. Significantly, in order to repair keyhole successfully and then obtain high quality joint, the design of pinless tool is very important. In this study, according to research results in our pre-experiment [24], six-spiral-flute shoulder was designed to improve material flow and six-spiral flutes distribute across a greater proportion of shoulder. Table 2 exhibits the feature, diameter and effective filling depth of rotational tool used in this experiment. The close-up photographs of these rotational tools are exhibited in Fig. 2. All the keyholes by tool with pin in Fig. 2a were produced in the sound magnesium alloy FSW joint under the rotational velocity of 1300 rpm and welding speed of 100 mm/min. The tensile strength and elongation of sound joint are 197.1 MPa and 6.6%, equivalent to 82% and 55% of BM, respectively. All the FSW and A-PFFSR experiments were performed using FSW-3LM-4012 machine. The tilt angle with respect of Z axis was 2.5°. During A-PFFSR process, the constant rotational velocity was 1300 rpm and the dwell time was 5 s. The plunge speeds were varied, which were 1 mm/min, 2 mm/min, 4 mm/min and 6 mm/min, respectively. During the PF process, in order to obtain surface formation and reduce or even eliminate possibility of kissing bond, pinless rotational tool moves forward along the welding direction after dwelling for 5 s. Before repairing, the workpieces and filler material were burnished using abrasive paper and cleaned by means of acetone in order to wipe off oxide layer.

After FSW and A-PFFSR experiment, the specimens were cut perpendicular to the welding line by an electrical discharge cutting machine to perform the mechanical test or microstructural characterization. The microstructure was etched by acetic picral (4.2 g picric acid, 10 ml H_2O, 10 ml acetic acid and 70 ml ethanol) and then observed by an optical microscopy (OLYMPUS, GX71). To evaluate mechanical property of FSW and A-PFFSR joints, three tensile specimens were prepared for each joint with reference to GB/T 2651–2008 (equivalent to ISO 9016: 2001) and the average value was presented for discussion [25]. Furthermore, tensile test at room temperature was performed under a constant crosshead speed of 3 mm/min. Microhardness of repaired specimen was measured by a micro-hardness tester at a load of 200 g for 10 s. In order to investigate hardness distribution through the thickness direction, one test line in each repairing layer across the cross-section

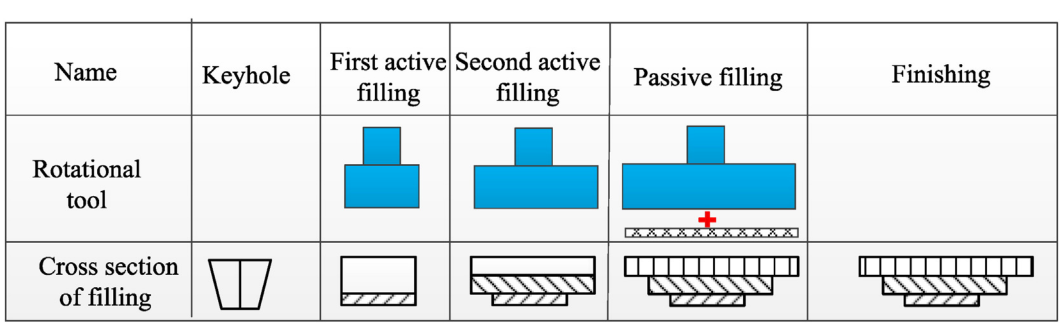

Fig. 1. Schematic diagram of A-PFFSR process.