

Microstructure and mechanical properties of friction stir weld of dissimilar AZ31-O magnesium alloy to 6061-T6 aluminum alloy

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Abstract: Dissimilar friction stir welding between AZ31-O Mg and 6061-T6 Al alloys was investigated. 3 mm thick plates of aluminum and magnesium were used. Friction stir welding operations were performed at different rotation and travel speeds. The rotation speeds varied from 600 to 1400 r/min, and the travel speed varied from 20 to 60 mm/min. Defect-free weld was obtained with a rotation speed of 1000 r/min and travel speed of 40 mm/min. Metallographic studies showed that the grain size in the stir zone is much finer than that in the base metals. Complex flow pattern was formed in the stir zone. Microhardness measurement revealed an uneven distribution in the stir zone. Tensile test results indicated that the tensile strength of the welded specimen is about 76% of AZ31 Mg alloy and 60% of the 6061 Al alloy in tensile strength. SEM fracture surface image of the welded specimen indicated that the welded specimen failed through brittle-mode fracture.

Key words: dissimilar frictions stir welding; AZ31-O Mg Alloy; 6061 Al alloy; microstructure; mechanical properties

1 Introduction

Weight reduction in automotive and aircraft industries is a main concern in improving fuel economy and reducing environmental pollutions [1,2]. Magnesium alloys, with a density of about two-thirds of Al alloys, are the promising engineering materials to boost fuel economy especially for the automotive industry [3,4]. Aluminum alloys are widely used in engineering fields due to their unique properties including high strength, good formability and low density [5]. Development of reliable joints between Al and Mg alloys will result in achieving a combination of Al and Mg properties [6]. Joining dissimilar metals through the fusion welding process is difficult due to the formation of brittle intermetallic compounds [7–9]. Friction stir welding (FSW) was invented at The Welding Institute (TWI) and is considered a solid-state welding process [10]. FSW between dissimilar metals has received much attention [11,12]. FSW between AZ31 Mg alloy and 1050 Al alloy was investigated by SATO et al [13], and the formation of intermetallic compound $Al_{12}Mg_{17}$ in the welding zone

was reported by these authors. YAN et al [14] investigated dissimilar friction stir welding between 5052 Al alloy and AZ31 Mg alloy. They reported uneven hardness distribution in the stir zone. SOMASEKHARAN and MURR [15] investigated microstructure in friction stir welding of AZ31/AZ91 Mg and 6061 Al alloys and reported the formation of complex flow pattern in the weld zone. The aim of this study is to investigate the microstructure and mechanical properties of the dissimilar friction stir welding between AZ31 Mg alloy and 6061 Al alloy.

2 Experimental

2.1 Base materials

3 mm thick plates of 6061-T6 Al and AZ31-O Mg were used in this study with the chemical compositions given in Table 1.

2.2 FSW of AZ31 Mg alloy to 6061 Al alloy

Prior to welding, a stainless steel brush was employed to remove surface oxides of the plates, and then the plates were cleaned with acetone (for cleaning

Table 1 Chemical Compositions of 6061 Al and AZ31 Mg alloy (mass fraction, %)

Alloy	Composition/%						
	Mg	Fe	Si	Mn	Cu	Al	Zn
6061 Al	0.8	0.4	0.54	0.07	0.2	Balance	–
AZ31 Mg	Balance	–	–	0.1	–	3	1

any surface pollutant). An unthreaded cylindrical tool made from H13 tool steel with a shoulder of 15 mm in diameter and concaved, a pin of 3 mm in diameter and 2.9 mm in length, and a tilt angle of 2.5° was used for the welding operation. Friction stir welding operations were performed at different rotation and travel speeds. The rotation speeds varied from 600 to 1400 r/min and the travel speeds varied from 20 to 60 mm/min. Butt welding operation was conducted, when 6061 Al alloy and AZ31 Mg alloy were placed at the advancing side (AS) and the retreating side (RS) of the tool pin, respectively. The pin wasn't offsetted with respect to the seam. All the tests including microstructural analysis, and tensile and microhardness testing were conducted on the welds obtained with the rotation speed of 1000 r/min and travel speed of 40 mm/min.

2.3 Microstructural analysis

Transverse cross section of the weld was prepared by polishing, and etching procedure was used by SOMASEKHARAN and MURR [15]. Picral etchant was used to etch Mg side of the weld and Keller etchant was employed to etch Al side of the weld. A solution of 5 mL HNO_3 in 95 mL distilled water was used to bring out the lamellar-like shear bands and fine microstructure in the intercalated weld zone. Picral and Keller etchant compositions are listed in Table 2. The microstructure of the weld was observed with an optical microscope.

Table 2 Chemical compositions of Picral and Keller etchant used (mL)

Etchant	Acetic acid	Picric acid	HNO_3	HCl	HF	Distilled water
Picral	2	14	–	–	–	2
Keller	–	–	3	6	6	150

2.4 Scanning electron microscopy

Elemental analysis of the weld and fracture surface fractography were performed using a VEGA II TESCAN scanning electron microscope (SEM).

2.5 Tensile test

Tensile test specimens were prepared according to the ASTM E8 with an electrical discharge machine

(EDM). The tests were carried out at room temperature using Instron 8502 test machine at a strain rate of 2 mm/min.

2.6 Microhardness testing

Microhardness measurements were performed with Shimadzu microhardness tester using a 0.49 N load and a dwelling time of 10 s.

3 Results and discussion

3.1 Microstructure of weld zones

Sound weld was obtained with a rotation speed of 1000 r/min and travel speed of 40 mm/min as shown in Fig. 1. All the tests including microstructural analysis, and tensile and microhardness testing were conducted on the welds obtained with these parameters (rotation speed of 1000 r/min and travel speed of 40 mm/min).

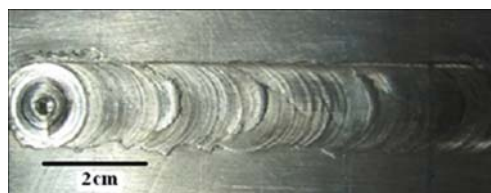
**Fig. 1** Top surface appearance of dissimilar weld between 6061 Al and AZ31 Mg alloy

Figure 2 shows the transverse cross-sectional macrograph of the weld. As shown in the picture, there is no porosity in the weld. This figure shows the microstructural zone including base materials (BM) and the stir zone (SZ); obvious thermomechanically affected zone (TMAZ) was found neither on the advancing side nor on the retreating side of the weld. Figure 3 shows the microstructures of different zones. The base material AZ31 consists of equiaxed grains with size ranging from 20 to 70 μm . The base material 6061 Al is seen to have elongated grains with an average size of 71 μm . Figures 3(c) and (d) show the intercalated microstructures of weld zone. These complex flow patterns have been seen in other dissimilar FSW welds [15–18] and comprise lamellar-like shear bands of Al and Mg alloy that have repeated intermittently. Figure 4 shows EDX maps of Al and Mg distribution in the intercalated microstructure of the stir zone. Figure 4 confirms that these flow patterns are composed of Al (blue colored in Fig. 4(c)) and Mg (green colored in Fig. 4(b)) shear bands; furthermore, Al and Mg alloys are swirled together and have formed an intermittent lamellar-like structure.

In the FSW process, dynamic recrystallization (DRX) occurs in the stir zone (SZ) due to the high strain rate applied to the material by the welding tool pin and

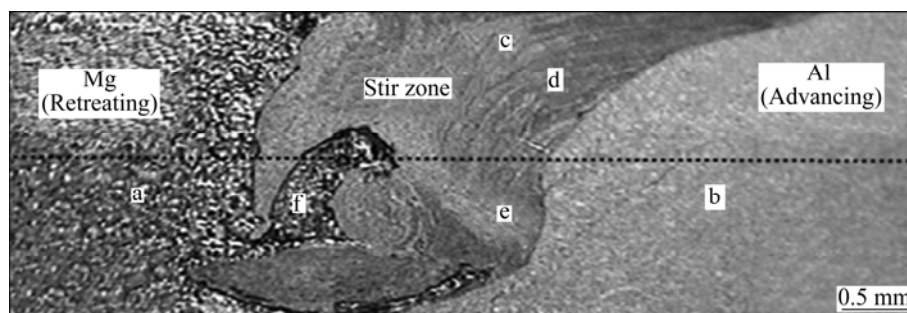


Fig. 2 Transverse cross-sectional macrograph of weld

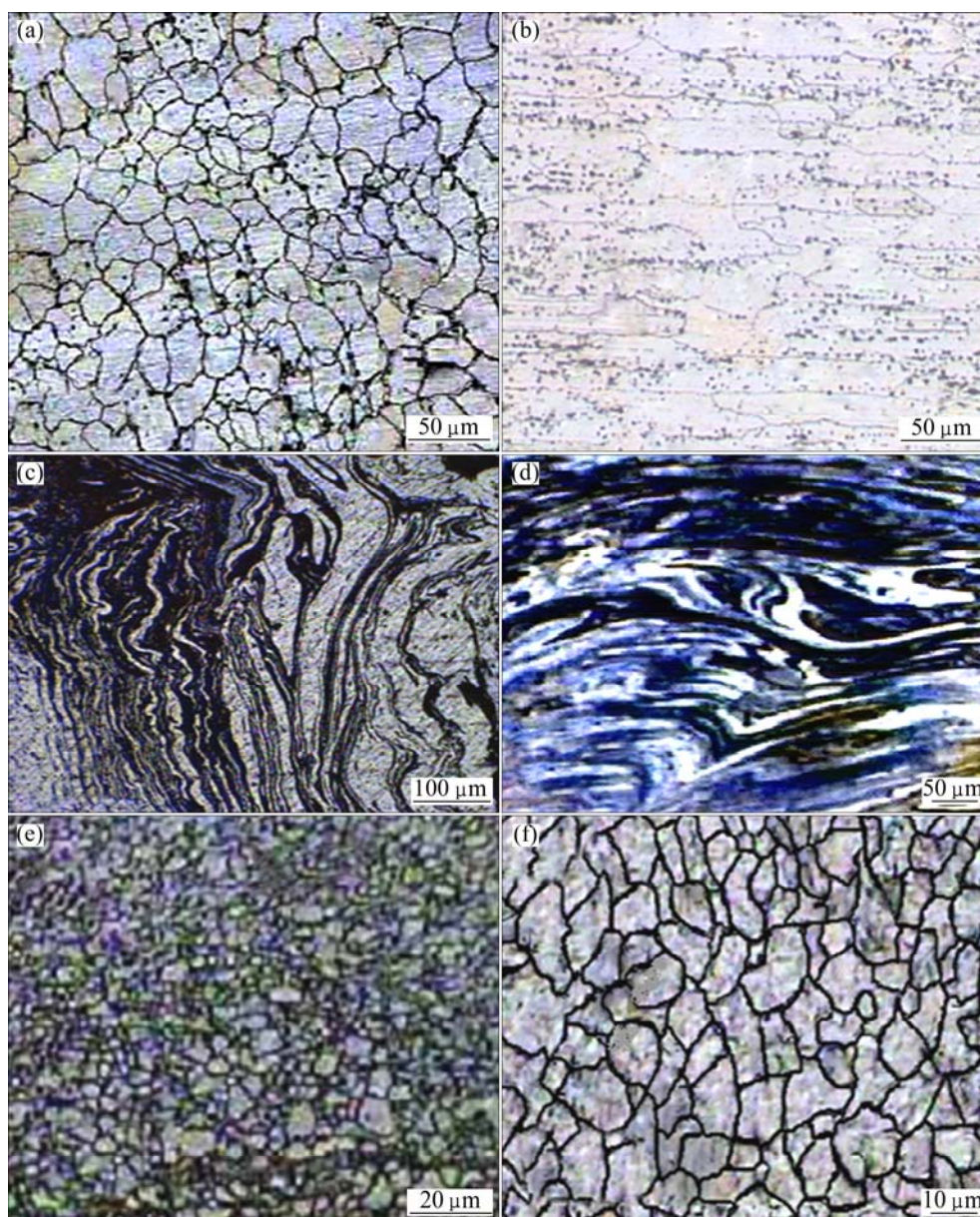


Fig. 3 Microstructures of different zones in Fig. 2: (a) AZ31 Mg base metal; (b) 6061 Al base metal; (c) Lamellar-like shear bands in weld zone; (d) Vortex flow-like intercalated microstructure; (e) Stir zone on Mg side; (f) Stir zone on Al side

the heat produced by friction between the material and the tool [19]. Figures 3(e) and (f) show the microstructures of regions (e) and (f) in the stir zone.

Regions (e) and (f) consist of fine equiaxed grains with an average size of 4.8 and 18 μm , respectively. Due to DRX, in these regions grain sizes are much smaller than

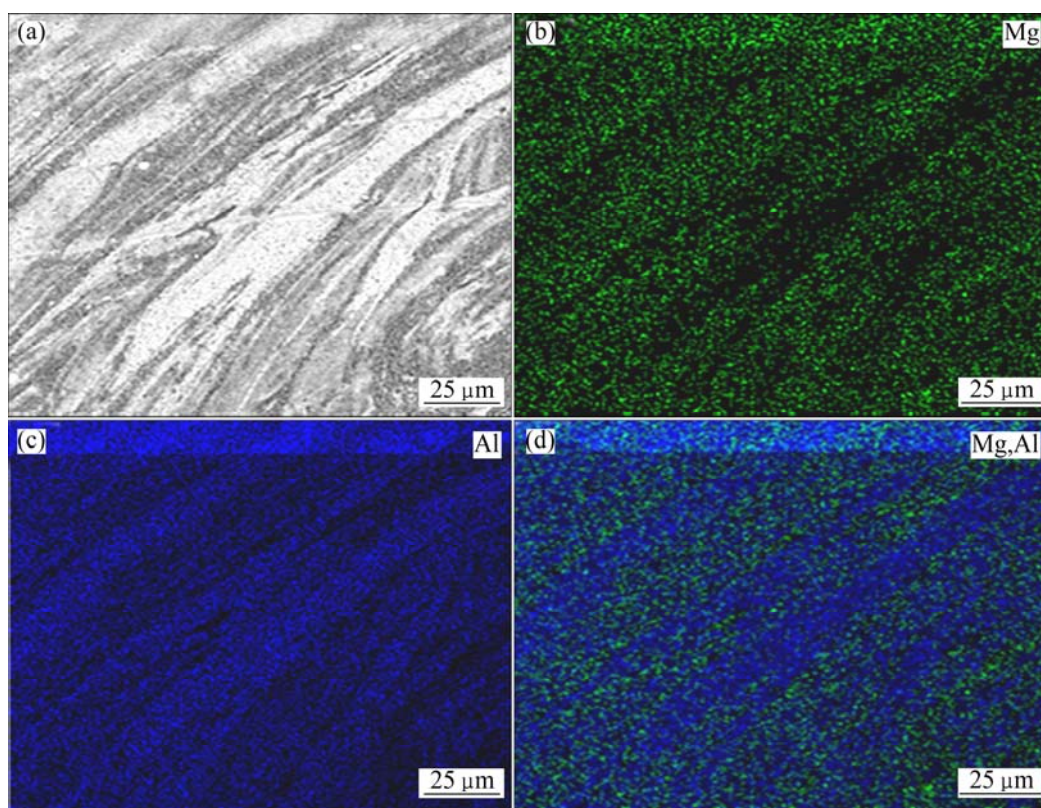


Fig. 4 Intermetallic microstructure of weld zone (a) and corresponding EDS maps (b–d)

those in the base materials.

3.2 Microhardness testing results

Figure 5 shows Vickers microhardness distribution along the dashed line shown in Fig. 2. The maximum hardness of HV 89 was measured in the stir zone and uneven hardness distribution was obtained in the stir zone. This uneven hardness distribution was reported in other dissimilar FSW between aluminum and magnesium alloys and the formation of the intercalated

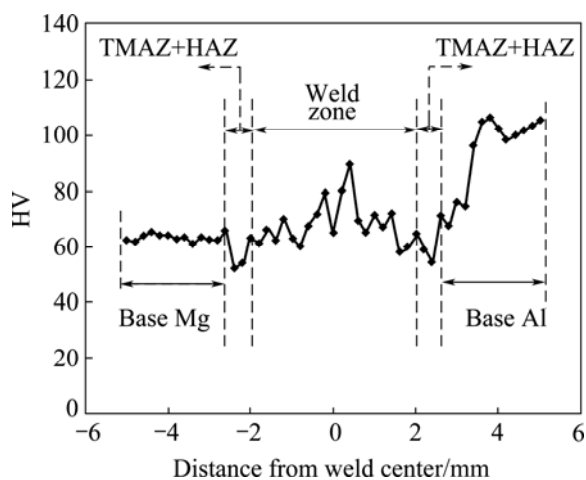


Fig. 5 Microhardness distribution along transverse cross section of weld in Fig. 2

microstructure was cited as the main cause of this uneven hardness distribution [14,15].

3.3 Tensile testing

The tensile properties of the base materials and the welded specimen are listed in Table 3. Tensile results indicate that the tensile strength of the welded specimen is about 76% of that of AZ 31 Mg alloy and 60% of that of 6061 Al alloy. Figure 6 shows SEM fracture surface images of the base materials and the welded specimen. The welded specimen failed at the joint center. The presence of dimples on the fracture surface of 6061 Al alloy (shown in Fig. 6(a)) indicates that the aluminum base metal failed through ductile-mode fracture. Quasi-cleavage fractured surfaces in Figs. 6(b) and (c) show that AZ31 Mg alloy and the friction stir welded specimen failed through brittle-mode fracture.

Table 3 Tensile properties of base metals and welded specimen

Specimen	Yield strength/MPa	Ultimate tensile strength/MPa	Elongation/%
6061 Al	235	295	12.5
AZ31 Mg	130	235	18.7
Weld	170	178	2.4

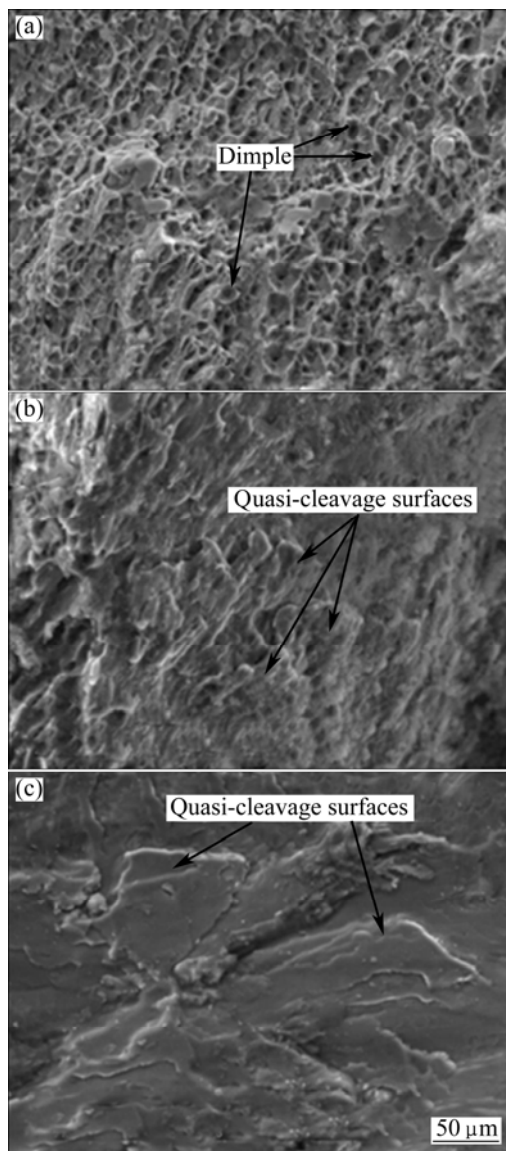


Fig. 6 SEM images of fracture surface: (a) 6061 Al base metal; (b) AZ31 Mg base metal; (c) Welded specimen

4 Conclusions

1) Defect-free weld between AZ31 Mg and 6061 Al alloy was obtained using friction stir welding with a rotation speed of 1000 r/min and travel speed of 40 mm/min.

2) Intercalated microstructure was formed in some regions in the stir zone, and this complex flow pattern may be responsible for the uneven microhardness distribution in the stir zone.

3) Grain refinement occurred in the stir zone due to dynamic recrystallization (DRX).

4) Tensile strength of the welded specimen was about 76% of that of AZ31 Mg alloy and 60% of that of 6061 Al alloy, and the welded specimen failed through brittle-mode fracture.

References

- [1] CAO X, JAHAZI M. Effect of welding speed on the quality of friction stir welded butt joints of a magnesium alloy [J]. *Materials and Design*, 2009, 30: 2033–2042.
- [2] SU S F, HUANG J C, LIN H K, HO N J. Electron-beam welding behavior in Mg–Al based alloys [J]. *Metallurgical and Materials Transactions A*, 2002, 33: 1461–1473.
- [3] BENARTZY A, MUNITZ A, KOHN G, BRINING B, SHTECHMAN A. Joining of light hybrid constructions made of magnesium and aluminum alloys [C]//*Magnesium Technology 2002*. Seattle, WA, USA: TMS, 2002: 295–302.
- [4] LIU L, WANG H, SONE G, YE J. Microstructure characteristics and mechanical properties of laser weld bonding of magnesium alloy to aluminum alloy [J]. *Materials Science*, 2007, 42: 565–572.
- [5] CHEN Y C, NAKATA K. Friction stir lap joining aluminum and magnesium alloys [J]. *Scripta Materialia*, 2008, 58: 433–436.
- [6] LIU C, CHEN D L, Bhole S, CAO X, JAHAZI M. Polishing-assisted galvanic corrosion in the dissimilar friction stir welded joint of AZ31 magnesium alloy to 2024 aluminum alloy [J]. *Materials Characterization*, 2009, 60: 370–376.
- [7] LEE W B, YEON Y M, JUNE S B. The mechanical properties related to the dominant microstructure in the weld zone of dissimilar formed Al joints by friction stir welding [J]. *Materials Science*, 2003, 38: 4183–4191.
- [8] PAGLIA C S, BUCHHEIT R G. Microstructure, microchemistry and environmental cracking susceptibility of friction stir welded 2219-T87 [J]. *Materials Science and Engineering A*, 2006, 429: 107–114.
- [9] CHANG W S, KIM H J, NOH J S, BANG H S. The evaluation of weldability for AZ31B-H24 and AZ91C-F Mg alloys in friction stir [J]. *Key Engineering Materials*, 2006, 321–323II: 1723–1728.
- [10] THOMAS W M, NICHOLAS E D, NEEDHAM J C, MURCH M G, TEMPLE-SMITH P, DAWES C J. Improvements to friction welding: Patent International 9125978.8[P]. 1991.
- [11] MCLEAN A A, POWELL G L F, BROWN I H, LINTON V M. Friction stir welding of magnesium alloy AZ31B to aluminum alloy 5083 [J]. *Science and Technology of Welding and Joining*, 2003, 8: 462–464.
- [12] SHIQEMATSU I, KWON Y J, SUZUKI K, IMAI T, SAITO N. Joining of 5083 and 6061 aluminum alloys by friction stir welding [J]. *Materials Science Letters*, 2003, 22: 353–356.
- [13] SATO Y S, PARK S H C, MICHUUCHI M, KOKAWA H. Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys [J]. *Scripta Materialia*, 2004, 50: 1233–1236.
- [14] YAN Yong, ZHANG Da-tong, QIU Cheng, ZHANG Wen. Dissimilar friction stir welding between 5052 aluminum alloy and AZ31 magnesium alloy [J]. *Transactions of Nonferrous Metals Society of China*, 2010, 20: 619–623.
- [15] SOMASEKHARAN A C, MURR L E. Microstructures in friction-stir welded dissimilar magnesium alloys and magnesium alloys to 6061-T6 aluminum alloy [J]. *Materials Characterization*, 2004, 52: 49–64.
- [16] FLORES R D, MURR L E, SHINDO D, TRILLO E A. Friction-stir welding of metals and alloys: Fundamental studies of solid-state and intercalated flow [C]//*Proceedings of International Conference on Processing and Manufacturing of Advanced Materials*. Las Vegas,

- NV: 2000: 4–8.
- [17] MURR L E, LI Y, TRILLO E A, FLORES R D, MCCLURE J C. Microstructures in friction-stir welded metals [J]. Materials Process Manufacturing Science, 1998, 7: 145–161.
- [18] YAN J C, XU Z W, LI Z Y, LI L, YANG S Q. Microstructure characteristics and performance of dissimilar welds between magnesium alloy and aluminum formed by friction stirring [J]. Scripta Materialia, 2005, 53: 585–589.
- [19] MISHRA R S, MA Z Y. Friction stir welding and processing [J]. Materials Science and Engineering R, 2005, 50: 1–78.

AZ31-O 镁合金和 6061-T6 铝合金 搅拌摩擦焊接头的显微组织和力学性能

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摘 要: 对 3 mm 厚的 AZ31-O 镁合金板和 6061-T6 铝合金板进行异种材料搅拌摩擦焊。实验中搅拌针的旋转速度为 600~1400 r/min, 前进速度为 20~60 mm/min。结果表明, 在旋转速度 1000 r/min、前进速度 40 mm/min 的工艺条件下, 可以获得无缺陷的焊接接头。组织观察发现搅拌区的晶粒尺寸要比基材区的明显小很多。在搅拌区形成了复杂的金属流动。显微硬度测试表明搅拌区的硬度分别是不均匀的。拉伸实验结果表明, 接头的拉伸强度约为基材 AZ31 镁合金的 76%, 或 6061 铝合金的 60%。接头拉伸断口 SEM 形貌观察表明为脆性断裂。

关键词: 异种搅拌摩擦焊; AZ31-O 镁合金; 6061 铝合金; 显微组织; 力学性能

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