Materials and Design 64 (2014) 74–80

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Investigation on dissimilar underwater friction stir lap welding of 6061-T6 aluminum alloy to pure copper

Jingqing Zhang, Yifu Shen *, Xin Yao, Haisheng Xu, Bo Li

College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA), Yudao Street 29, 210016 Nanjing, PR China

ARTICLE INFO

Article history:
Received 15 June 2014
Accepted 18 July 2014
Available online 26 July 2014

Keywords:
Underwater
Friction stir welding
Dissimilar
Temperature history
Intermetallic compounds

ABSTRACT

Friction stir welding (classical FSW) is considered to offer advantages over the traditional fusion welding techniques in terms of dissimilar welding. However, some challenges still exist in the dissimilar friction stir lap welding of the aluminum/copper (Al/Cu) metallic couple, among which the formation of the Al–Cu intermetallic compounds is the major problem. In the present research, due to the fact that the formation and growth of the intermetallic are significantly controlled by the thermal history, the underwater friction stir welding (underwater FSW) was employed for fabricating the weld, and the weld obtained by underwater FSW (underwater weld) was analyzed via comparing with the weld obtained under same parameters by classical FSW (classical weld). In order to investigate the effect of the external water on the thermal history, the K-type thermocouple was utilized to measure the weld temperature, and it is found that the water could decrease the peak temperature and shorten the thermal cycle time. The XRD results illustrate that the interface of the welds mainly consist of the Al–Cu intermetallic compounds such as $CuAl_2$ and Cu_9Al_4 together with some amounts of Al and Cu, and it is also found that the amount of the intermetallic in the underwater weld is obvious less than in the classical weld. The SEM images and the EDS line scan results also illustrate that the Al–Cu diffusion interlayer at the Al–Cu interface of the underwater weld was obviously thinner than that of the classical weld.

1. Introduction

Many hybrid components have been widely used in aerospace, nuclear, transportation and electronics industries, especially for the aluminum/copper (Al/Cu) metallic couple. However, the physical and mechanical properties of both metals are significantly different. As a consequence, some challenges still exist in the dissimilar welding. The major problem arises from the chemical affinity at temperatures higher than 120 °C, which could lead to the formation of the Al/Cu brittle intermetallic phase and low melting point eutectics [1]. Thus, the solid joining processes have been considered as the qualified welding methods for these metals [2,3].

Friction stir welding (FSW) is a novel solid joining technology invented by the welding institute (TWI) in 1991 [4]. This welding technology has initially been developed for aluminum alloys, and soon spread to many other materials and materials combinations. Since its discovery, FSW technique has been widely applied in aerospace, shipbuilding, electronics and railway industries [5–7].

Comparing with the conventional fusion joining techniques, FSW owns many advantages [8]. During this welding process the peak temperature is lower than the metal melting point, and it has the excellent ability to weld dissimilar metals. Since its discovery, many researchers have focused on the dissimilar FSW.

Abdollah-Zadeh et al. [9] studied the microstructural and mechanical properties of friction stir welded aluminum/copper lap joints. They observed the various microstructures with different morphologies and properties in the stir zone. It is found that Cu_9 Al_4, CuAl and Cu Al_2 are the main intermetallic compounds formed in the interfacial region. A high heat input could increase the amount of intermetallic compounds and then decreased the mechanical properties. Even so, the heat input should not be too low, because an extremely low heat input could result in the imperfect joint. Ouyang et al. [10] investigated the microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper. They concentrated on the relationship between the temperature distribution and the intermetallic. It is also found the intermetallic compounds such as $CuAl_2$, CuAl and Al_4Cu_9 together with small amounts of α-Al and the saturated solid solution of Al in Cu exist in the mechanically mixed region. The primary dendrites of α-Al, $CuAl_2$, CuAl and the eutectic of α-Al/$CuAl_2$ are formed in the weld nugget during solidification. They perfectly explained the

* Corresponding author. Tel.: +86 025 84895940; fax: +86 2552112626.
E-mail addresses: jingqing_zhang@hotmail.com (J. Zhang), yifushen@nuaa.edu.cn (Y. Shen).

http://dx.doi.org/10.1016/j.matdes.2014.07.036
0261-3069/

phases present in the welds basing on the Al–Cu binary phase diagram. Galvão et al. [1] analyzed the influence of aluminum alloy type on dissimilar friction stir welding of aluminum to copper. They chosen the AA 6068 (a heat-treatable aluminum alloy) and the AA 5083 (a non-heat treatable aluminum alloy to be friction stir lap welded to copper. They studied the differences in welding results of the two type aluminum basing on the macro and microscopic analysis, and obtained many useful and meaningful conclusions for the investigation on the friction stir lap welding of aluminum to copper.

Despite the excellent ability of the FSW for jointing dissimilar Al/Cu metals, intermetallic compounds are still a major problem. From the previous works, it can be concluded that three factors influence the welding results. Primarily, a suitable flow of the softened material contributes to the complete formation of the weld. Extremely low rotational speed or high welding speed always results in imperfect joints. Secondly, cracking tends to incidence in intermetallic-rich zones, which is the major reason for the premature failure of dissimilar Al/Cu friction stir welds. The formation and growth of intermetallic compounds depend on the local peak temperature and the length of the incubation period, respectively. Low welding temperature and short incubation time could contribute to decrease the amount of the brittle intermetallic compounds. Thirdly, during the FSW, which is also a hot working process, the dynamic recovery and recrystallization mechanisms are still applied [11], thus, it is necessary to control the formation and growth of the grain. For the classical FSW process, it is difficult to take the three factors into account at the same time. However, this situation would become different when the process is conducted in a water circumstance, because the external liquid accelerates the heat dissipation, and then affects the thermal cycles. This modified FSW process is named underwater friction stir welding (underwater FSW) [9]. For the convenience of discussion, the weld obtained by classical FSW is called classical weld and that obtained by underwater FSW is called underwater weld.

In recent years, the underwater FSW has been demonstrated to be available for the strength improvement of classical welds. Liu et al. [12] studied the mechanical properties of underwater FSWed 2219 aluminum alloy. They found that compared with the classical weld the tensile strength of the underwater weld can be indeed improved, however, the plasticity is deteriorated. Then they further investigated the effect of welding speed and rotation speed on microstructures and mechanical properties of underwater FSWed 2219 aluminum alloy [13,14]. The results reveal that the precipitate deterioration in the thermal mechanically affected zone and the heat affected zone is weakened with the increase of welding speed, which leading to a narrowing of softening region and an increase in lowest hardness. It is also found that the joint welded at lower rotation speed tends to be fractured in the SZ, and at higher rotation speeds, the hardness increase in the stir zone (SZ) makes the fracture locations of defect-free joints move to the thermal–mechanically affected zone (TMAZ) or heat affected zone (HAZ). Zhao et al. [15] analyzed the microstructure and mechanical properties of spray formed 7075 aluminum alloy by underwater friction stir welding. The results show that tensile strength and hardness of the underwater weld are higher than that of the classical weld, and the underwater weld has a fine grained microstructure without "S line" defect. Zhang et al. [16] developed a three-dimensional heat transfer model of underwater FSW of high strength aluminum alloy. The simulation and experimental results indicate that, in contrast to the classical weld, the maximum peak temperature of underwater weld is significantly lower, although the surface heat flux of the shoulder is higher during the respective welding process. It is also found that the high-temperature area could be dramatically reduced, and the welding thermal cycles in different zones could be effectively controlled by the external liquid (flowing water).

Currently, Al/Cu underwater FSW has been less explored than the Al/Cu classical FSW, especially for the lap welding. In the present work, based on the potential industrial applications of this metallic couple, a feasibility investigation of lap joining 6061 aluminum alloy to pure copper by underwater FSW was performed. The thermal histories, macrostructure and intermetallic compounds of the underwater weld were analyzed by comparing with the classical weld.

2. Experimental procedures

As illustrated in Fig. 1, the pure copper plate (2 mm-thick, 100 mm-width, 200 mm-length) was placed at the top of 6061-T6 aluminum alloy plate (8 mm-thick, 100 mm-width, 200 mm-length), this configuration enables copper cladding over small areas. [1]. In order to better study the underwater FSW process, under the same welding parameters (as listed in Table 1), two experiments were conducted under water and in air, respectively. The friction stir welding tool consists of two parts: the concave shoulder and the conical unthreaded pin. The tool schematic sketch is shown in Fig. 2 and the tool shape dimensions are presented in Table 2.

For the dissimilar (underwater) friction sir lap welding process, the thermal history and peak value at the interface of the two metals significantly influenced the welding results. Thus, in this investigation, K-type thermocouples were utilized to measure the temperature. The schematic diagrams of thermocouples locations are shown in Fig. 3. The thermal histories of classical FSW were measured by thermocouples K1, K2 and K3, and the thermal histories of underwater FSW were monitored by thermocouples Ka, Kb and Kc. It is noteworthy that the temperature distribution between the advancing side (AS) and retreating side (RS) is asymmetric, and it is skewed to the AS and toward the leading edge of the tool [17–19]. Considering this asymmetric temperature distribution, the thermocouples were located in the AS.

After welding, the welds were characterized by the optical microscopy, the X-ray diffraction (XRD), and the energy dispersive spectroscopy (EDS).

3. Results and discussion

3.1. Thermal histories

During the FSW process, the weld heat is principally generated at the tool shoulder by the frictional heating, and the friction coefficient is adjusted so that the peak temperature did not exceed the melting temperature, thus, in the present work, the heat was mainly generated by the friction between the copper and the tool shoulder, and due to the heat absorption capacity of water is rather higher than that of air, the two FSW process present obviously different thermal cycle characters.

The thermal histories of classical FSW and underwater FSW are shown in Fig. 4a and b, respectively. It can be found that the peak temperature exists within the region close to the tool pin, and for the classical FSW it is ∼850 K while for the underwater FSW it is ∼821 K. It is worth mentioning that the melting point of the Al–Cu eutectic or some of the Al–Cu hypo-eutectic and hyper-eutectic alloys is ∼825 K [10,20]. In the case of the peak temperature, during the classical FSW process, the high temperature (∼850 K) and long incubation time (∼15 s) could lead the formation and growth of the Al–Cu eutectic alloys. However, for the underwater FSW, the external water distinctly decreased the peak temperature value, and it should be able to prevent the formation of the intermetallic.

In addition, comparing with the classical FSW thermal history (Fig. 4a), the measured temperature of the underwater FSW