Fatigue behavior of Al-Al and Al-steel refill friction stir spot welding joints

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1. Introduction

Lightweight is one of the most important directions in the global development of new energy mobility [1] . Several concepts were developed as: (1) Hybrid sandwich metal-plastic structure[2] ; (2) High strength/weight ratio alloys[3,4] ; (3) Material joining, e.g. self-piercing riveting (SPR)[5] , electric resistance welding (ERW)[6] and friction stir welding (FSW)[7,8] .

FSW has achieved outstanding welding properties, but the key-holes within the joint will bring in a weak bonding interface[9] and poor mechanical stability[10] . To overcome the above challenges, refill friction stir spot welding (RFSSW) was proposed and developed[11] , which works on similar Al-Al and dissimilar Al-steel metallic joints[7] , as well as metal-polymer composites[12] . Owing to the welded metallic structure often suffers vibration and other damages during long-term service, the fatigue properties and failure mode of RFSSW joint needs to be careful examination before real application[13] . Therefore, the fatigue testing and failure analysis shall be carried out. As the physical properties between Al and steel are different, the joint interface shall have different effects on the fatigue behavior. The present research shall accelerate the design of similar and dissimilar materials joining under RFSSW process.

2. Experimental procedure

The studied materials include Aluminum (Al 1060) and steel (DIN 1623) sheets, cleaned and grinded, with thickness of 2.0 mm and area of 50 x 150 mm. The welding was conducted using RFSSW machine provided by Aerospace Engineering Equipment (Suzhou) Co., Ltd. The sequence of the welded joint from up to down is Al and steel, as well as the overlap area is 50 x 50 mm. The critical processing parameters and processes were: (1) rotation speed: 2000 RPM; (2) penetration depths 2.40 and 1.85 mm for Al-Al and Al-steel joints; (3) penetration speed: 1 mm/s. It shall be noted that the refill material comes from the upper sheet. The joint locates in the center position of the overlap area, and the joint diameter is 9 mm.

After welded, the cross-section of Al-Al and Al-steel joints were electron spark cut and polished for hardness test, where hardness was measured along the welding seam, upper and lower sheets (1 mm distance from the welding seam) using Vickers indenter. The load was 0.245 N and a dwell time of 10 s. The Al-Al and Al-steel specimens were tensile tested by Zwick/Roell Z250 with a strain rate of 1mm/min. The tension-tension fatigue tests were conducted using sinusoidal wave in load control mode with R=0, and the testing frequency was 30 Hz by Instron 8801. The stress amplitude ($\Delta\sigma=(\sigma_{max}-\sigma_{min})/2$) was set as 0.2, 0.3 and 0.4 of the joint shear strengths (σ_b) to quantitative analysis and comparison. After the fatigue test, all the specimens were stretched to fracture for observing fatigue damages.

3. Results and discussion

The hardness distribution of Al-Al joint is shown in Fig. 1(a). In the regions of welding seam, as well as upper and lower sheets, the hardness value varies from 23 to 28 HV. However, the hardness distribution of the Al-steel joint varies much as displayed in Fig. 1(b). The welding seam and lower steel sheet exhibit higher hardness between 120 and 150HV, while the upper Al sheet's hardness is only about 30 HV, resulting in inhomogeneous hardness distribution.

The static overlap-shear strengths (σ_b) of Al-Al and Al-steel joints are 4691 N and 3846 N, respectively. The higher shear strength of Al-Al joint shall be resulted from the higher penetration depth and more solid mixture of similar materials. To quantitatively compare the fatigue behaviors of Al-Al and Al-steel joints, the stress amplitudes ($\Delta\sigma$) were set as 0.2, 0.3 and 0.4 of the joint shear strength. The testing results are illustrated in Figs. 1(c&d), where both the Al-Al and Al-steel RFSSW joints exhibit reliable fatigue properties, compared with other reported results[14,15]. It is noted that the Al-steel joint with $\Delta\sigma/\sigma_b$=0.2 does not suffer obvious damages after 10^5 cycles.

3.1 Al-Al joint

Figures 2 (a&b) illustrate the detailed OM observation of the fatigue fracture with $\Delta\sigma/\sigma_b$=0.2. Two fatigue patterns are found: (1) the fatigue striations exhibit circumference direction along the RFSSW joint, where commonly observed in the front of joint, i.e. the fatigue crack initiation region (Fig. 2(a)); (2) the fatigue striations have the path penetrating the thickness direction, which close to the torn fracture region (Figs. 2(b).

With $\Delta\sigma/\sigma_b$increasing to 0.3 as shown in Figs. 2(c&d), the fatigue striations also exhibit two different types with circumference and thickness directions. However, the fatigue striations along thickness direction get more obvious and these striations approach to the fatigue crack initiation region. With $\Delta\sigma/\sigma_b$ further increasing to 0.4 (shown in Figs. 2(e&f)), the fatigue striations along thickness direction is detected in both crack initiation and torn fracture regions.

The present observation of fatigue behaviors of Al-Al RFSSW supports that the joint significantly influenced by stress amplitude. The higher stress amplitude is, the more obvious fatigue striations, along thickness direction, are. Besides, the fatigue striations along thickness direction cover the fatigue striations with circumference direction located in the crack initiation region. This fatigue behavior transition shall be attributed to the higher stress concentration around the RFFSW joint., rather than the interface between Al-Al layers.

3.2 Al-steel joint

Figures 3(a&b) illustrate the OM observation of both the Al sheet and steel sheet fatigue fractures with $\Delta\sigma/\sigma_b$=0.3, respectively. It is found that fatigue striations exist in the edge of the joint, starting from the Al part of the joint. With $\Delta\sigma/\sigma_b$ increasing to 0.4, the fatigue striations are both found from the Al sheet and steel sheet parts as show in Figs. 3(c&d). The present observation supports that the effect of secrete hardness distribution within the Al-steel joint plays a more important role in fatigue crack initiation position rather than that of the parameter of $\Delta\sigma/\sigma_b$ does.

4. Conclusions

The fatigue behavior of Al-Al and Al-steel RFSSW joints are systemically studied, and several conclusions are listed as below:

1. Al-Al RFSSW joint has homogeneous hardness distribution across the welding seam, but Al-steel RFSSW joint has discrete hardness distribution.

2. With stress amplitude or $\Delta\sigma/\sigma_b$ increasing, the stress concentration within the joint of Al-Al joint grows, resulting in the fatigue striations with thickness direction gets more obvious in the crack initiation region.

3. The similar Al-Al RFSSW joint is significantly influenced by stress amplitude, while the fatigue behavior of dissimilar Al-steel joint is insensitive to stress amplitude.

4. Regardless of stress amplitude or $\Delta\sigma/\sigma_b$ varying, Al-steel RFSSW has discrete hardness distribution, leading to fatigue crack initiation from edge of Al-steel joint.

The current observation of the fatigue properties and behavior of similar Al-Al and dissimilar Al-steel RFSSW joints shall accelerate the lightweight design for vehicle industry.

Declaration of competing interest

The authors declared that they have no conflicts of interest in this work.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contribution Statement

H.K. and D.T designed the experiments and wrote the manuscript. J.X. and C.Y. performed optical microscope observation. Y. and H.S. carried out the tensile and fatigue test. W.W. helped shape the research, analysis and manuscript.

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