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Effects of mechanical heterogeneity on the tensile and fatigue behaviours in a laser-arc hybrid welded aluminium alloy joint

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ABSTRACT

The effects of mechanical heterogeneity on the tensile and high cycle fatigue (10^4–10^7 cycles) properties were investigated for laser-arc hybrid welded aluminium alloy joints. Tensile–tensile cyclic loading with a stress ratio of 0.1 was applied in a direction perpendicular to the weld direction for up to 10^7 cycles. The local mechanical properties in the tensile test and the accumulated plastic strain in the fatigue test throughout the weld's different regions were characterized using a digital image correlation technique. The tensile results indicated heterogeneous tensile properties throughout the different regions of the aluminium welded joint, and the heat affected zone was the weakest region in which the strain localized. In the fatigue test, the accumulated plastic strain evolutions in different subzones of the weld were analyzed, and slip bands could be clearly observed in the heat affected zone. A transition of fatigue failure locations from the heat affected zone caused by accumulated plastic strain to the fusion zone induced by fatigue crack at pores could be observed under different cyclic stress levels. The welding porosity in the fusion zone significantly influences the high cycle fatigue behaviour.

1. Introduction

Due to multiple aspects of laser-arc hybrid welding, its high welding speed, precise heat input, low accumulated stress and increased welding process stability, it is a highly attractive joining technique when compared to conventional welding methods; furthermore, it's validation has been confirmed through numerous studies [1,2]. Laser-arc welding is particularly suitable for joining aluminium alloys because of its welding efficiency and its ability to avoid metallurgical defects in the weld. The heat flow produced by both the laser and the arc leads to the variation of thermo-mechanical conditions within the joint and creates a heterogeneous microstructure, and as a result, the local mechanical properties are not uniform across the weld [3,4]. Moreover, the global tensile and fatigue behaviours of the welded joints depend upon the local microstructures and basic mechanical properties, such as the strength and ductility. Consequently, it is very important to clarify the relationship between the local mechanical properties and the global fatigue behaviours of the welds.

As for approaches for determining the local mechanical properties of welds, the hardness test is the most well-known and widely used technique. The mechanical properties of the welded region can be obtained from the relationship between the flow stress and microhardness [5,6]. In addition, digital image correlation (DIC) is another method for characterizing the local mechanical behaviours of different sub-zones and the global response of the welds [7–13]. Reynolds et al. [10] was one of the first to apply this method for the determination of the constitutive behaviours of welded joints. Then, Genevois et al. [7] and Lockwood et al. [8] combined this full-field local strain measurement and numerical modelling to characterize the mechanical properties of friction stir welds, assuming an iso-stress configuration during the transverse tensile weld sample loading. Previous studies on the heterogeneous properties of welded joints primarily focused on the tensile properties. However, few researchers investigated the effects of mechanical heterogeneity on the fatigue behaviour of laser-arc hybrid welded aluminium alloy joints.

In the present paper, both tensile and fatigue tests were performed on laser-arc hybrid welded aluminium alloy joints. Both the local mechanical properties in the tensile tests and the accumulated plastic strain in the fatigue tests throughout the weld's different regions were investigated using a digital image correlation technique. An optical microscope (OM) and a scanning electron microscope (SEM) also served to characterize the local cumulative plastic deformations of different subzones during the fatigue test. Finally, the fatigue failure mechanism was discussed with consideration given to the mechanical heterogeneity and welding porosity.

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2. Experimental methods

1A80 aluminium plates (base material) with a thickness of 2 mm and 4043 filler wires were used in the welding process. Their chemical compositions (in weight percentage) are shown in Table 1. The welding direction was placed parallel to the rolling direction of the base materials, and the schematic diagram of the welding process is shown in Fig. 1. Furthermore, the angle between the laser beam and the arc torch was fixed at 30°; other welding parameters are presented in Table 2. Full-size transverse tensile and fatigue specimens were machined from the welded plates so that the weld was centered in the gauge section, and the loading axis was normal to the welding direction. The dimensions of the specimen are presented in Fig. 2. To void the effect of weld profile on the stress concentration during the tensile and fatigue test, the weld reinforcement was sanded with sandpaper prior to being tested. For microstructural observations, the specimens were electrochemically polished by a solution of phosphoric acid and alcohol and then observed by optical microscopy (OM) during the test.

Tensile and fatigue tests were performed on a 450 N electromagnetic machine operating at room temperature. A force controlled loading mode was applied with a loading speed of 1 N/s in the tensile test. Fatigue tests were performed with a stress ratio of 0.1 and a frequency of 50 Hz. One of the specimen's surfaces was prepared by applying a random speckle pattern using black and white spray paints in order to determine the strain field by digital correlation. This technique proved to be a practical method for determining both the displacement and deformation fields of an object surface [14,15]. A CCD camera with a resolution of 1280 * 1024 pixels was used to record the un-deformed and deformed specimen surfaces during the test. A self-programmed analytical software was used to calculate the displacement and strain fields with a grid of 30 × 30 pixels (1 pixel = 5 μm). The hardness measurement of the entire weld region with a spacing of 0.25 mm was conducted using a Vickers indenter with a load of 0.98 N and a dwell time of 15 s.

3. Results and discussion

3.1. Microstructure and hardness profile

A macroscopic view of the cross section of the laser-arc welding zone is shown in Fig. 3a. The welded joint can be divided into three zones: the fusion zone (FZ), the heat affected zone (HAZ) and the base material (BM). Since the as-received BM is in the rolled state, most of the grain orientations are parallel to the rolling direction, as shown in Fig. 3b. However, in the HAZ, the rolled grains disappear, which indicates that the recrystallization occurred close to the FZ during the welding process. In Fig. 3c, a fine grained dendritic microstructure with many precipitates (Mg_2Si) at the grain boundaries is observed in the FZ. This dendritic microstructure is generally found in a laser-arc hybrid welded Al alloy [16]. The formation of this fine grained microstructure in the FZ was attributed to the high solidification rates during the laser-arc hybrid welding, which is beneficial for retaining the re-solidified aluminium's strength [17].

The micro-hardness profile, in the form of nephogram, throughout the weld joint is illustrated in Fig. 3d. It is evident that the hardness obviously decreases in the HAZ, similar to that of arc welding [18], where overaging takes place as a result of heat input during the weld process. Furthermore, the hardness decrease in the HAZ was higher than that in the HAZ formed in the laser beam welds [19] but was lower than that in the arc welding [18]. The micro-hardness in the FZ is higher than that in the HAZ and BM because of the brittleness phase (Mg_2Si) of high hardness.

Table 1
Chemical composition (wt.%) of base metal and filler wire.

Materials	Si	Fe	Cu	Mn	Mg	Ti	Zn	Al
1A80	0.15	0.15	0.03	0.02	0.02	0.03	–	Remainder
4043	4.8	00.8	0.3	0.05	0.05	0.2	0.1	Remainder

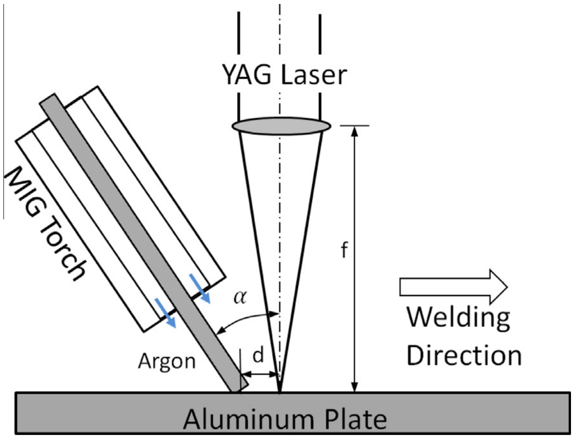

Fig. 1. Schematic diagram of the YAG laser-MIG hybrid welding system.

3.2. Local mechanical behaviours in tensile test

The tensile test was applied to the weld in the transverse direction. The local strain field was calculated by the DIC method from the weld region of 2 × 9 mm^2 as illustrated in Fig. 4a. The nominal strain, ε_n, and the nominal stress, σ_n, of the global stress–strain curve in Fig. 4a were calculated as:

$$\varepsilon_n = \frac{l - l_0}{l_0}, \sigma_n = \frac{F}{A_0} \qquad (1)$$

where l and l_0 are the actual and initial length, F is the applied force and A_0 is the initial cross-section of the specimen. At a stress of 70 MPa, the corresponding local strain fields throughout the weld are also present in the inset in Fig. 4a. It reveals that the three sub-zones of the weld, the BM, FZ and HAZ, experience different deformation behaviours, with the HAZ undertaking the highest strain because of the material softening. Lookwood et al. produced similar strain localization results for the friction stir welded AA2023 [9]. Based on the local strain fields measured by the DIC, it is possible to obtain a complete description of the actual material behaviour in the different weld zones, assuming an iso-stress configuration [8] in the tensile test. The local strains of the three points located in the BM, FZ and HAZ are extracted and plotted in Fig. 4b against the corresponding nominal stress, σ_n. It can be seen that the constitutive relations of the three points are almost the same when the loading stresses are below their respective yield stresses. The stress of the BM goes up linearly with a slope of 6.94×10^{10}, keeping a state of elasticity in the test. Consequently, the yield stress of the BM is not reached, and it is not possible to determine its value. The 0.2% offset yield strength of the FZ is about 42.5 MPa, which is higher than that of the HAZ (37.5 MPa) that corresponds to the formation of coarse grains after welding. These zones actually show a larger ductility than the BM and HAZ, with the strain localisation occurring accordingly in the HAZ [7]. Therefore, with the increasing of loading stress, the HAZ goes into plastic state first, and then fracture finally occurs in the tensile test.