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Failure modes and fatigue behavior of conventional and refilled friction stir spot welds in AA 6061-T6 sheets

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ABSTRACT

The fatigue behavior of conventional friction stir spot welding (FSSW) and friction stir spot welding refilled by the friction forming process (FSSW-FFP) in aluminum 6061-T6 lap shear specimens, are investigated based on the experimental observations. Optical micrographs of the welds after fatigue failure in both the cases are examined to study the fatigue crack propagation and failure modes. Experimental results indicate that the fatigue strength of the FSSW-FFP weld samples is higher than that of the conventional FSSW samples at all loads. Fracture surfaces are analyzed in detail using the scanning electron microscope.

1. Introduction

Aluminum is an ideal material for transport applications, because of its high strength to weight ratio, corrosion resistance and very good thermal and electrical conductivity. It also plays an important role in reducing CO_2 emissions in transportation helping to improve the sustainability of the transport industry. In recent years automotive manufacturers are making good use of the wide variety of aluminum products, such as the extruded aluminum tubes in space frame structures, and aluminum sheets for inner and outer panels. Weight reductions of 50% for the 'body in white' have been achieved by the substitution of steel by aluminum [1,2]. Alloy 6061 is one of the most widely used alloys in the 6000 Series. This standard structural alloy, one of the most versatile of the heat treatable alloys, is popular for medium to high strength requirements, and has good toughness characteristics. Applications range from transportation components to machinery and equipment, to recreation products and consumer durables.

Notably, the Resistance spot welding (RSW) of aluminum is more complex than that of steel because aluminum's higher thermal conductivity requires higher power and current requirements [3]. However, the RSW of aluminum sheets is likely to produce poor welds as reported by Thornton et al. [4] and Gean et al. [5]. Recently, a new spot friction welding (SFW) technology for joining aluminum sheets has been developed by Mazda Motor Corporation and Kawasaki Heavy Industry [6,7]. Latabhai et al. [8] indicated that the shear strength first increased and then decreased, with increasing tool rotational rate for AA6061-T5 FSSW joints, while Tozaki et al. [9] reported that the tensile shear strength monotonically increased with increasing tool rotational rate [10]. Wang et al. [11] studied the microstructures and failure mechanisms of friction stir spot welds in aluminum 6061-T6 lap-shear specimens, using optical micrographs.

Most of the friction stir spot welded components used in the automobile and aerospace industries are subjected to fatigue loads in service conditions. It is very essential to study the fatigue behavior of these components. Limited studies are available regarding the failure modes and fatigue behavior in friction stir spot welded aluminum alloys. Lin and Pan have investigated the failure modes and fatigue life of the conventional FSSW lap shear specimens in aluminum 6111-T4 sheets [12,13]. They have adopted the fatigue crack growth model, to estimate the fatigue lives of spot friction welded samples, and compared them with the experimental results [14,15]. Tran et al. [16] investigated the fatigue behavior of dissimilar spot friction welds in aluminum 5754-O and 6111-T4 lap-shear specimens under quasi-static and cyclic loading conditions. Wang et al. [17] investigated the fatigue lives of friction stir spot welds in aluminum 6061-T6 lap-shear specimens under cyclic loading conditions. Tran et al. [18] investigated the fatigue behavior of dissimilar friction stir spot welds in lap-shear and cross-tension specimens of the aluminum 6000 series alloy and coated steel sheets, under quasi-static and cyclic loading conditions [19]. Lin et al. [20] investigated the failure modes and

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fatigue life estimations of spot friction welds in cross-tension specimens of aluminum 6061-T6 sheets under quasi-static and cyclic loading conditions.

However, most of the literature available till now, discusses only the fatigue behavior in conventional FSSW samples. Fatigue literature on the refilled friction stir spot welding is scant. Y. Uematsu and K. Tokaji studied the effect of refilling the probe hole on the tensile failure and fatigue behavior of friction stir spot welded joints in the Al–Mg–Si alloy [21]. They reported that the tensile strength of the joint with the re-filled probe hole was higher than that of the joint with the probe hole, but the fatigue strength of the joint with the re-filled probe hole was nearly the same as, and lower than, at low and high applied loads, respectively, that of the joint with the probe hole [21]. The friction forming process was invented by one of the present authors and the patent was granted in the year 2008 [22]. Based on the friction forming process, a new friction spot welding process was reported by John Prakash and Muthukumaran, known as friction stir spot welding, with refilling by the friction forming process (FSSW-FFP) [23]. The FSSW-FFP was modified by adding an additional plate called the filler plate, and effective refilling and higher static shear strength was achieved as reported in [24].

In this paper, the fracture and fatigue behaviors of conventional FSSW and FSSW-FFP welds in aluminum 6061-T6 lap shear specimens are investigated based on the experimental observations. Optical micrographs of the welds after failure under cyclic loading conditions are examined, to understand the dominant fatigue cracks, and the fatigue crack propagation in both conventional FSSW and FSSW-FFP. Based on the optical micrographic observations of the paths of the dominant kinked fatigue cracks, the kinked fatigue cracks responsible for the fracture of a weld sample are analyzed, and the different failure modes of the weld samples in conventional FSSW and FSSW-FFP under low and high cycle loading conditions are then investigated. Finally, the fatigue lives of both conventional FSSW and FSSW-FFP are compared, based on the experimental results. The fracture surface of the failed fatigue specimens were analyzed in detail using the scanning electron microscope (SEM).

2. Experimental procedure

In this investigation, aluminum 6061-T6 sheets of 2 mm thickness were welded using the conventional FSSW and FSSW-FFP. In conventional FSSW, tool having a shoulder with a diameter of 18 mm and a pin diameter of 5 mm. The schematic representation of the FSSW-FFP is shown in Fig. 1. This process involves basically two steps, namely, extrusion and refilling. Extrusion tool was similar to the conventional FSSW tool but the pin length was more. Friction forming tool having a shoulder with a diameter of 18 mm was used for the refilling process. The three plates (one filler plate and two work pieces) are placed one above the other and this whole assembly is placed on a backing plate. The first step involves forcing a rotating tool through a sheet metal work piece. The frictional heating at the interface between the tool and work piece enables the softening, deformation, and displacement of the work material and creates a bushing projection in the bottom plate leaving behind a probe hole in the top plate, as shown in Fig. 1c. The rotational tool was lowered and suitable plunge depth was given as soon as shoulder touches the filler plate. Once the shoulder crosses the filler plate, the filler plate was separated from the assembly. This is followed by reversal of the remaining two plates for the next step i.e., the refilling operation. In the refilling, the bush type material which had come out during the first step is plunged back by the friction forming tool, as shown in Fig. 1d and e. The tool rotational speed is used in refilling is same as that

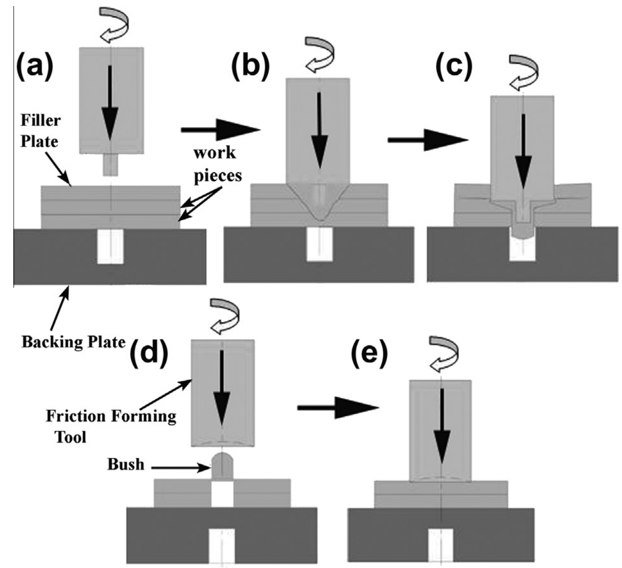

Fig. 1. Schematic illustration of the FSSW-FFP.

used in the extrusion process. The welding parameters are summarized in Table 1. The detailed micrographic analysis of the weld samples of both the processes before testing can be found in [24].

The dimensions of the test specimen are maintained same in both static as well as fatigue tests in conventional FSSW and FSSW-FFP welds. The specimen length, width, overlapping length and grip length are 100 mm, 30 mm, 30 mm and 30 mm, respectively. In the present investigation, the optimal processing parameters specified in [24] and as shown in Table 1 were used to make the conventional FSSW and FSSW-FFP weld samples. Table 2 shows the static shear strength of the conventional FSSW and FSSW-FFP weld samples at different tool rotational speeds. A higher static shear strength is observed at 900 rpm and 1800 rpm for the conventional FSSW and FSSW-FFP respectively. Hence, for the fatigue studies, weld samples made of 900 rpm for the conventional FSSW and 1800 rpm for FSSW-FFP were chosen. The average failure loads specified in [24] were used as the reference values to determine the loads applied in the fatigue tests. The usual procedure for determining the maximum stress applied in the fatigue test was limited to about two-thirds of the static tensile strength of the material [25].

Fatigue tests were performed by using the BiSS nano UTM machine operating at a sinusoidal frequency of 4 Hz and load ratio of 0.1. Two specimens were tested for each load range, and the number of cycles to failure was obtained by averaging those of the two individual specimens. The tests were terminated when the specimens failed. Some of the tests were terminated before failure, in order to observe the fatigue crack growth behavior of the weld samples. Some of the tests were terminated beyond the 1.5×10^6 cycles, due to the limited operating time of the testing machine. The micrograph of the partially failed material was used to observe the fatigue crack growth behavior, and different failure modes in the conventional FSSW and FSSW-FFP weld samples. The fracture surfaces were analyzed in detail using the scanning electron microscope. A graph was plotted to compare the fatigue strengths of the conventional FSSW and FSSW-FFP weld samples.

3. Failure modes under cyclic loading conditions

3.1. A two dimensional general overview of the failure modes

The experiments were conducted under cyclic loading conditions for the conventional FSSW and FSSW-FFP weld samples. In