2014/2219 Tri-Point Crack Analysis

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Karla Renee Horton

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Abstract

Friction stir welding (FSW) is a solid state welding process with potential advantages for aerospace and automotive industries dealing with light alloys. Self-reacting friction stir welding (SR-FSW) is one variation of the FSW process being developed at the National Aeronautics and Space Administration (NASA) for use in the fabrication of propellant tanks. Friction plug welding is used to seal the exit hole that remains in a circumferential SR-FSW.

The objective of this study was to evaluate the deformation response at the tips of cracks located in the heat affected zone of friction plug welds and to study the fracture behavior of welds with defects in the form of fatigue cracks. The study used existing 2014-T6 to 2219-T87 self-reacting friction stir weld panels with 2219-T87 friction plug welds. Electro-discharge machined (EDM) notches were machined into the heat affected zone of the plug at the plug-to-base metal interface. Samples were then cycled to generate a fatigue crack emanating from the notch. After the fatigue crack reached a pre-defined length, a speckle pattern was applied and the ARAMIS® system (a three dimensional imaging correlation system) was used to measure the deformations at the crack tip under a sequence of loads. Testing was conducted at ambient laboratory conditions.

Fracture data from the testing was analyzed to evaluate residual strength capability of the panel as a function of flaw size. ARAMIS® strain data was evaluated to examine strain and deformation patterns that develop around the crack tip and at the plug/weld interfaces. Four samples were used in this study, with three samples in a post-weld heat treated condition. Three samples contained large diameter plugs (M5) and one sample contained a small diameter plug (M3). Two samples were 4 inches in width and two samples were 8.5 inches in width. All samples failed through the precrack with residual strengths ranging from 37 ksi to 42 ksi.

Introduction

Friction-stir welding (FSW) is a solid-state joining process invented and patented by The Welding Institute (Thomas, Nicholas et al. 1991), a British research and technology organization. The process is applicable to aerospace, shipbuilding, aircraft and automotive industries. Two key benefits of this new technology are it allows aluminum alloys to be welded together that cannot be readily fusion arc welded, the traditional method of welding, and, in general it creates stronger welds than fusion arc welding.

FSW utilizes frictional heating combined with forging pressure to produce high-strength bonds virtually free of defects. FSW transforms the metals from a solid state into a "plastic-like" state, and then mechanically stirs the materials together under pressure to form a welded joint. A schematic illustrating the friction stir weld process is shown in Figure 1. In self-reacting FSW, there are two rotating shoulders: one on top (or front) and one on the bottom (or back) of the workpiece. A threaded shaft protrudes from the tip of the pin to beyond the back surface of the workpiece. The back shoulder is held axially in place against tension by a nut on the threaded shaft.

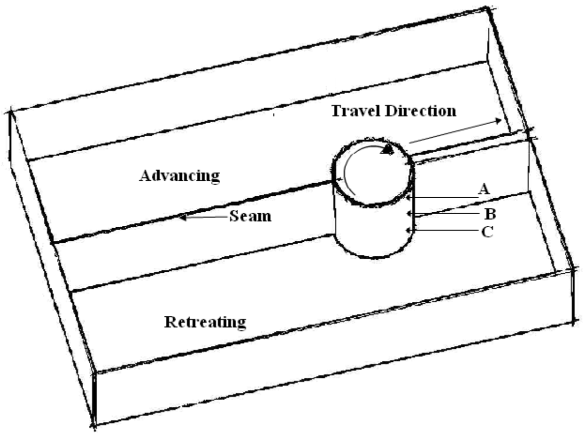

Figure 1. Schematic of Friction Stir Weld Process

The main axial force exerted on the workpiece by the tool and front shoulder is reacted through the back shoulder and the threaded shaft, back into the FSW machine head, so that a backing anvil is no longer needed (Tech Briefs, 2006). The opposing forces balance, simplifying the backup tooling required for making welds in tanks.

During longitudinal FSW, the tool travels off the workpiece to excess material at the end of the panel that is later trimmed off to remove any hole left by the friction stir weld tool. However, many components in the aerospace industry require a circumferential frictional stir welds which leaves an exit hole in the metal when the tool is removed. A process called friction plug weld (FPW) is used to plug the exit hole. Friction plug welding is an innovative weld repair technique whereby a hole is drilled through the weld at the location of the exit hole. A rotating tapered plug is then welded into the hole. The complete conical section of the tapered plug is welded to the surface of the drilled hole almost simultaneously. Considerable heat is generated, and the plug and work piece are welded together. Excess plug protruding from the repaired hole is removed and the surface is prepared for non-destructive inspection. A photograph of samples containing friction plug welds is shown in Figure 2.

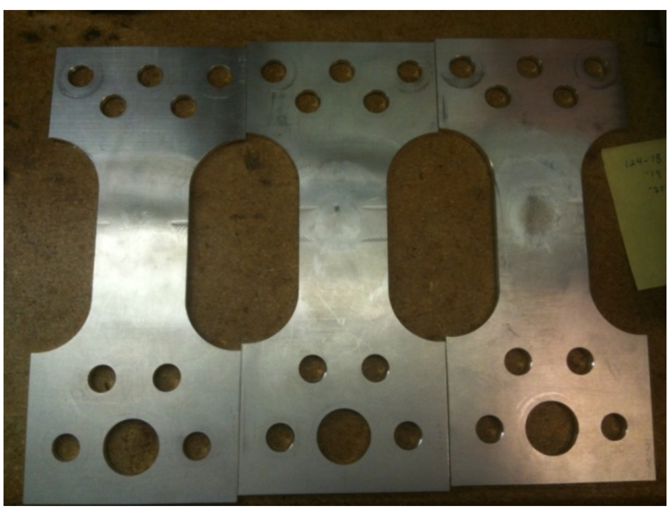

Figure 2 Friction Plug Welds in Test Samples

Experimental

The study examined the deformation response at the tips of cracks located in the heat affected zone of friction plug welds and the fracture behavior of welds with defects in the form of fatigue cracks. The study used existing 2014-T6 to 2219-T87 self-reacting friction stir weld panels with 2219-T87 friction plug welds. Electro-discharge machined notches were machined into the heat affected zone of the plug at the plug-to-base metal interface. The sample was cycled to generate a fatigue crack emanating from the notch. After the fatigue crack reached a pre-defined length, a speckle pattern was applied and the ARAMIS® system was used to measure the deformations at the crack tip under a sequence of loads. Testing was conducted at ambient laboratory conditions.

Results

Four samples were tested in this study. Table 1 outlines the test matrix for the specimens showing the pre-crack length, the EDM notch length, test environment, plug size, flaw location and if the specimen was in the PWHT condition. Each sample was intended to be notched at the tri-point area (TP) were the plug, initial weld and base metal intersected. The notch was successfully placed on three of the samples. One sample was notched slightly inward, toward the plug.

Each sample was precracked then a speckle pattern was applied before testing. Figure 3 shows the precrack in sample CX05-P2 and the applied speckle pattern used for imaging during testing. All samples were tested in the same manner. The three specimens with the larger flaws had a residual strength of 37, 39 and 39 ksi which is approximately 71% of the strength of a weld with no flaw. The specimen with the smaller flaw had a residual strength of 42 ksi which is approximately 78% of the strength of a weld with no flaw. The estimated surface crack stress intensities (K_{Ie}) were an average of 22.5 ksi-√in for the larger flaws and 17 ksi-√in for the smaller flaw. Detailed test results are shown in Table 2.

Figure 4 shows photographic images of sample CX05-P1 specimen after failure showing the minor diameter side, speckle pattern and the fatigue pre-cracked flaw in the specimen. The ARAMIS® imaging results, detailed in Figure 5 shows strain results from sample CX05-P1 which indicate a large strain accumulation on the retreating side of the weld with the greatest concentration of strain at the crack traveling along the weld through the plug. Figure 6 shows the crack growth along the weld through the plug.

Conclusions

Residual strengths were measured for friction plug weld samples in 2014/2219 self-reacting friction stir welds with fatigue pre-cracked flaws at the tri-point. Various plug diameters and post weld conditions were evaluated. The flaws ranged from 0.200 inches to 0.400 inches in length with residual strengths ranging from 37 ksi to 42 ksi. As expected, residual strengths varied inversely with flaw size. Although the database is very limited, it appears that residual strength is not affected by plug diameter, but may be influenced by post weld heat treat condition.

Specimen	Width [in]	PreCrack [in]	EDM Notch [in]	Test Environment	Plug Flaw Location	L/R	PWHT
CB 180-P3	4”	0.380	0.33	RT	M3 Major TP Ret	Left	N
CB 185-P2	4”	0.380	0.33	RT	M5 Major TP Ret	Right	Y
CXO5-P1	8.5”	0.380	0.33	RT	M3 Major TP Ret	Right	Y
CXO5-P2	8.5”	0.200	0.15	RT	M3 Major on Plug Ret	Right	Y

Table 1. Test matrix for first pathfinder test series of 2014/2219 M3 and M5 plug welds

Figure 3. Sample CX05-P2 with EDM notch and applied speckle pattern.

Specimen	PWHT	Plug	2c (inches)	a (inches)	Test Temp (°F)	Failure Location	Residual Strength (ksi)	K_{Ie} Estimate ksi√in
CB 180-P3	N	M3	0.402	0.181	70	Precrack	37	22
CB 185-P2	Y	M5	0.390	0.175	70	Precrack	39	23
CXO5-P2	Y	M3	0.394	0.181	70	Precrack	39	23
CXO5-P2	Y	M3	0.213	0.100	70	Precrack	42	17

Table 2: Residual Strength of 2014/2219 M3 and M5 Friction Plug Welds

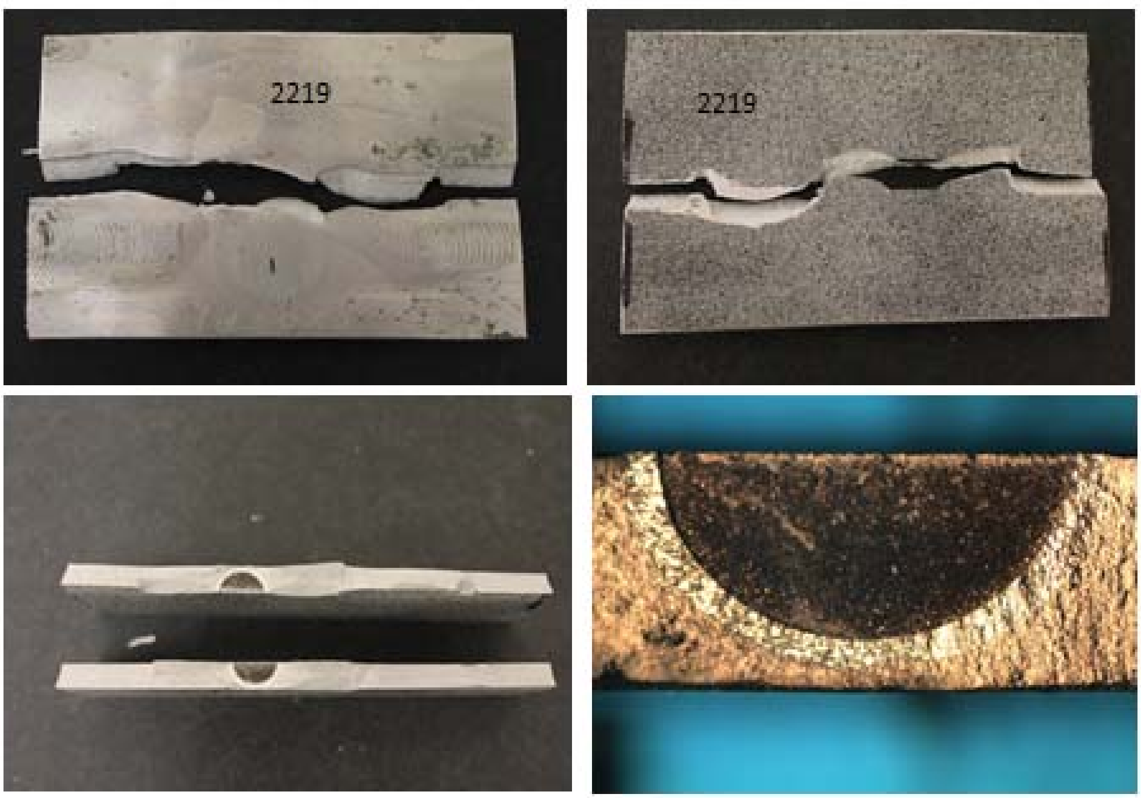

Figure 4. Sample CX05-P1: Top Left - the minor diameter side of the specimen; Top Right - the major diameter side with speckle pattern; Lower Left – pre-cracked flaw and fracture surface across part of the sample; Lower Right – close up of EDM notch and pre-cracked flaw.

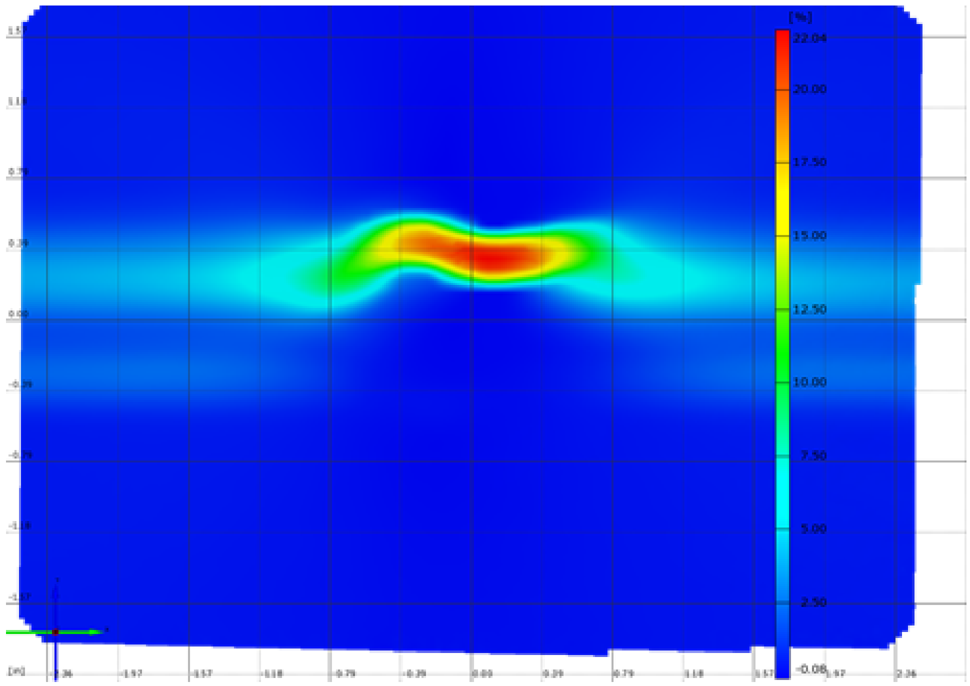

Figure 5. Strain pattern in sample CX05-P1 showing large strains at the crack (red region) with an accumulation of strain along the weld heat affected zone on the retreating side of the initial weld.

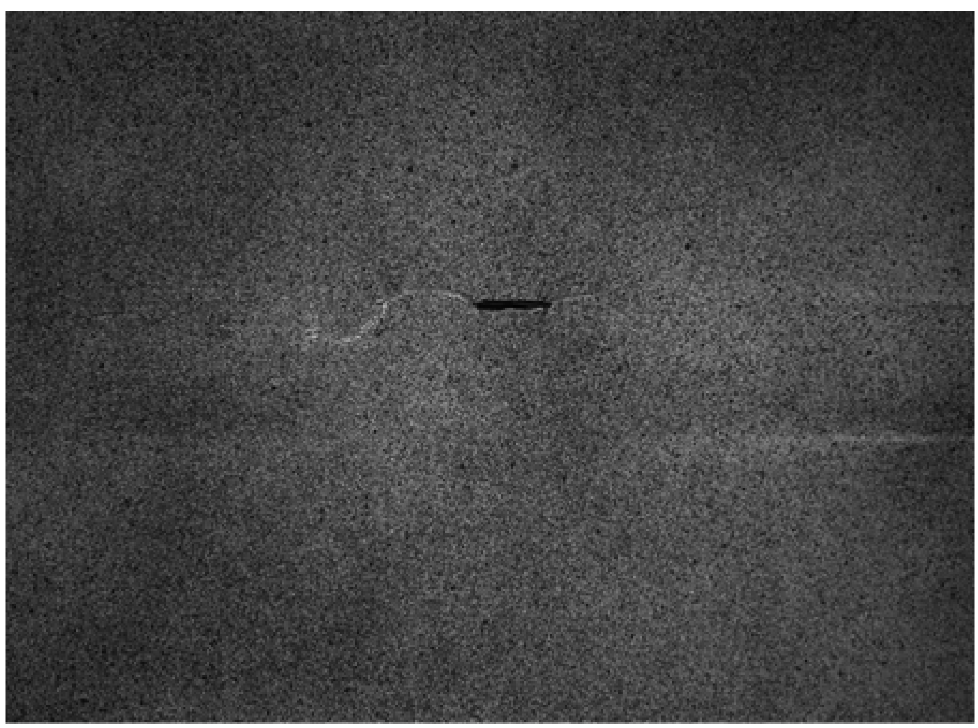

Figure 6. Photograph of sample CX05-P1 with crack growth through the plug.