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Fatigue behavior of friction stir spot welding and riveted joints in an Al alloy

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Abstract

The main aim of this study was to compare the fatigue resistance of welded joints produced by FSSW process and riveted joints of AA2024 alloy. The specimens welded with the best preliminary parameters determined by previous tensile shear tests were tested in fatigue under load control, R=0.1, at room temperature. Two welding parameter sets were used, and P-N curves (load versus cycles) were plotted, using $2x10^6$ cycles as the fatigue life limit. A similar curve was obtained for riveted specimens. The FSSW welding procedures were carried out in a CNC milling machining and the riveted specimens were produced in accordance with aircraft industry parameters. Although the welded specimens presented almost the same results in the tensile shear tests, the results were fairly lower than those observed for riveted joints in fatigue. The main failure mode observed in the welded joints was shearing, besides some cases of crack propagation in the perpendicular load direction, while for riveted specimens occurred mainly fretting nucleation followed by crack propagation in the perpendicular load direction. The evidences of shearing and lower fatigue lives for welded specimens indicate that the joint geometry highly affects the joint properties, due probably to stress concentrators presented locally.
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Keywords: FSSW; fatigue; riveted joints; failure modes.

1. Introduction

Friction Stir Spot Welding (FSSW) is a process developed recently and has been studied for applications in automotive, aeronautic and other industries [1]. This welding technology is quite similar to Friction Stir Welding process (FSW), and the main difference is the type of joint. In FSSW, the plates form a lap-joint and the tool penetrates the plates only in a point. In the FSW process the plates are positioned in a butt-joint configuration and the tool moves towards the joint direction. Therefore, the FSSW process can be explained in three distinct steps: plunging, stirring and retracting. The process initiates with the tool plunging slowly, then the heat and the rotation promote the stirring and finally the tool is retracted [2]. The retracting step is performed rapidly, just after the tool

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has reached the plunge depth or after a dwell time, that is a period in which the tool just turns in the maximum plunge depth [3].

During the process the heating caused by the friction softens the material; the rotation of the tool pin is responsible for the flow of material which occurs in the radial and axial directions, and the pressure applied by the head of the tool allows the welding formation in the solid state. At the end of the process, after the tool's retraction, a characteristic hole is observed [3]. Due to the short period spent in the welding (2 to 5 s), the tool plunging motion determines basically the heat generation, the joint formation, the weld mechanic properties, and the formation of the plastically deformed material, helping the bond around the pin [4].

FSSW mimics the resistance spot welding process (RSW) and can be used to replace bond processes, such as riveting, RSW, screwing and any other punctual method. FSSW overcomes the inherent difficulties found in other methods, as high cost for fasteners, longer downtime caused by feeding issues and need for other operations (e.g. drilling) [5].

The mechanical properties and microstructures of FSSW welded joints have been studied to evaluate the parameter's process effects. The main parameters studied were plunge rate, rotational speed, plunge depth and dwell time. Another relevant parameter is the axial force during the welding. Some authors have measured the axial force generated in FSSW [3, 4, 6]. On the other hand, it can be used axial force control with tool plunge rate fluctuation [7]. Although both processes are possible, the first is mostly applied due to its easiness. The mechanical properties measured in most works are restricted to tensile shear tests [3, 7, 8], however cross-tension tests have also been cited [9].

Concerning fatigue tests, an interesting study using AA 6111-T4 alloy covered tensile shear and fatigue tests [10, 11]. Two different tool geometries, flat and concave, were evaluated and in both tests the concave tool generated the best results. Other aspects discussed in the study were failure modes, microstructural analysis and a life prediction model. Tran et al [12] also studied failure modes and a life prediction model using welding joints in tensile shear and fatigue tests, and Chang et al [13] examined the failure modes in tensile shear tests.

Three distinct failure modes were observed for the samples tested in tensile shear: tear fracture, plug fracture and shear fracture [13]. A tear fracture mode was observed in the most resistant joints followed by plug fracture. Both failure modes occurred in the interface between the thermo-mechanically affected zone and the thermally affected zone. Shear fracture mode was linked to the worst results, and in this case the weld ring suffered shear.

In the fatigue tests the failure modes occurs in a more complex way. Lin et al [10, 11] and Tran et al [12] observed failure modes caused in both fatigue and tensile shear tests. Lin et al [10, 11], used a flat tool and verified a shear fracture in the tensile shear tests and low-cycle fatigue tests. In the high-cycle fatigue tests two types of cracks appeared, both starting at the tip of the bonded region. On the other hand, using the concave tool, no shear fracture was observed, and in all tests the specimens presented cracks (in the stir zone for the tensile shear tests and in the base material for the fatigue tests). These observations explained the best results yielded by the concave tool, due to a different geometry profile.

The present study aimed to evaluate the fatigue behaviour of two sets of samples welded by FSSW process. Furthermore, riveted joints were also tested for comparison, as riveting is the mostly used technique in the aeronautic industry to join aluminum based plates, in which the AA2024 alloy is usual. The characterization of failure modes was also performed for riveted and welded joints.

2. Materials and Methods

Lap shear specimens riveted and friction stir spot welding were prepared using AA2024-T3 alloy, 60x40x1,6 mm plates and 40x20 mm overlap. The welding process was performed in a CNC milling cut using parameters based on a previous study [14]. Two sample sets were welded changing only the plunge depth parameter (2.85 and 3.1mm). A 10 mm in diameter flat tool with a pin of 2.3 mm length and 4 mm in diameter were employed. The material used was the H13 steel, and the pin was heat treated and carbonitrated. A concave profile tool was also tested in a preliminary study. However, the results of tensile shear tests in the specimens welded with a concave profile tool were poorer [14]. Table 1 shows the parameters used in each set of specimens, named WAxx and WBxx. The riveted joints (RAxx) were fabricated at TAM Company, Brazil, using the same specifications of aircraft maintenance: AA2117-T4 alloy with MIL-C-5541 superficial treatment, 4.0 mm diameter and 100º ± 30' countersink.

Table 1. FSSW parameters used to prepare the welded joints.

Specimens	plunge depth	plunge rate	RPM	dwell time
WA	2.85 mm	2 mm/s	4000	4 s
WB	3.10 mm	2 mm/s	4000	4 s

The fatigue tests were performed in an MTS test machine, in load control, R=0.1 and a frequency of 20Hz. End tabs were added to the riveted and welded specimens, in order to avoid bending. A total of $2x10^6$ cycles was established as the fatigue limit and the highest load used was adjusted to generate a minimal life near 10^4 cycles. The failure modes of the welded and riveted joints were identified and photographed. Analyses were performed to verify the presence of cracks in the riveted joints that failed by the rivet shear.

3. Results and Discussion

Table 2 presents the maximum load used during the fatigue tests. The load values were determined based on a previous tensile study and on the criteria explained above. The averages of the tensile shear failure load of the joints in the preliminary study were 6.4 kN for riveted joints (RA), and 5.45 kN for WA and 4.95 for WB for FSSW welded joints.

Table 2. Maximum loads applied during the fatigue tests.

Specimens	Smax (kN)
RA 02	5.8
RA 01, 05 and 12	5.15
RA 03, 06 and 10	4.5
RA 04, 08 and 09	3.85
RA 07, 11 and 13	3.22
WA 05, 08 and 14; WB 02, 05 an 14	2.73
WA 04, 10 and 16; WB 01, 06 an 12	2.18
WA 02, 07 and 13; WB 03, 07 an 15	1.64
WB 04 and 10	1.36
WA 01, 12 and 15; WB 08	1.09

Figure 1 presents the curves of maximum load vs. fatigue life until specimen failure. The welded joints supported proportionally lower loads than the riveted joints under the fatigue tests, considering the tensile shear results as a reference. The maximum loads in the riveted joint tests were approximately twice that used in the welded joints to achieve the same lives, as the rivet is homogeneous while the welded material presents only a heterogeneous metallurgical bond. This heterogeneity is caused by microstructural changes with a consequent decrease in hardness due to the overaging. Another analysis could also be performed concerning the stresses concentrator factor, as the region where the welds end seems a crack, concentrating more stress than the hole used in the rivet process. Finally, comparing the two types of FSSW welded joints the results were similar; however the WB joints presented longer lives, contrary to the tensile tests, in which the WA joints presented the best results. This finding is probably due to the mechanical anchoring caused by the higher penetration in the WB specimens.

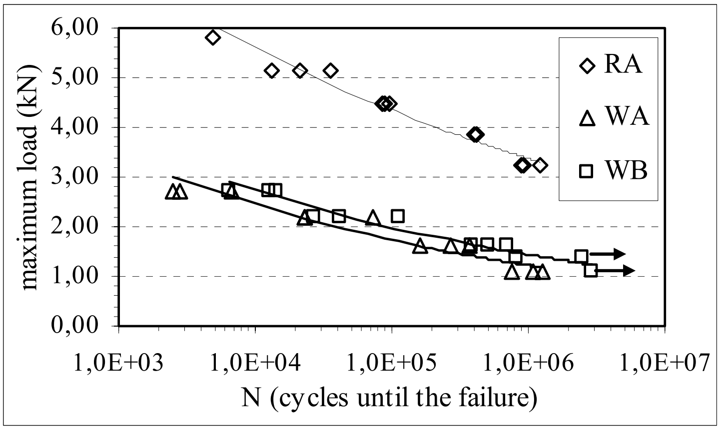


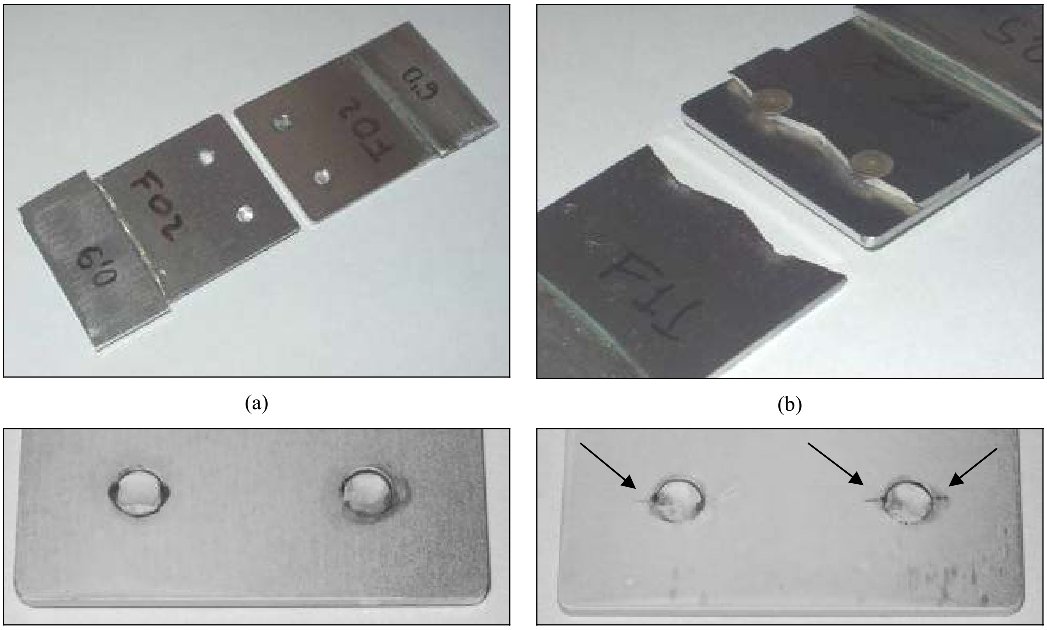
Fig. 1. Failure modes observed in the fatigue tests.

No comparison between the properties of welded joints and riveted joints has been found in the literature. However, some studies covering tensile and fatigue tests can be used to evaluate the performance of the welded joints of the present study regarding the quality of the fatigue results. Lin et al [10, 11] also studied two sets of FSSW welded joints fabricated with different tools, named concave and flat tools. The flat tool leads to 1.94kN in the tensile shear tests. In fatigue tests, applying nearly 1kN (~50% of maximum tensile load) the specimen reached 10^4 cycles and using approximately 0.8kN (~40% of maximum tensile load) the tested specimen attained 10^5 cycles. The samples fabricated with the concave tool supported a higher load in the tensile tests (2.59 kN); in the fatigue tests with 1.2kN applied as the maximum load (~46% of maximum tensile load) a 10^4 cycle life was obtained, and tests with 0.8kN (~31% of maximum tensile load) provided nearly 10^5 cycles. In the present study the maximum loads supported in the tensile tests were 5.45 kN for WA and 4.95 for WB. In fatigue tests, the WA specimens supported 2.2 kN (~40% of maximum tensile load) to 10^4 cycles and 1.64 (~30% of maximum tensile load) to $2x10^5$ cycles, and the WB specimens supported 2.73 kN (~55% of maximum tensile load) to 10^4 cycles, and 1.64 kN (~33% of maximum tensile load) to $4x10^5$ cycles. Considering fatigue results and the tensile shear test results as reference, this work obtained near the same results of Lin et al [10, 11]. The WA specimens reached the shortest lives, i.e., lives similar to those observed by Lin et al [10,11] for specimens fabricated using a flat tool. On the other hand, the WB specimens presented the best results in a range close to Lin et al [10,11] results while using the concave tool. Tran et al [12] results were also in the same level of loads and lives for two materials, AA5754-O and AA6111-T4, presenting around 50% of the maximum load in the tensile shear tests for 10^4 cycles, and 30% for 10^5 cycles. Thus, these comparisons show the low resistance in fatigue of the welds produced by the FSSW process when compared to tensile shear results. For instance, the riveted joints supported 80% of the maximum tensile load for a life of 10^4 cycles, and 70% for almost 10^5 cycles.

Regarding failure modes the welded and riveted joints presented two different fractures depending on the applied load. Table 3 presents the failure mode operating in each specimen. Riveted joints failed due to rivet shearing or fretting crack nucleation followed by crack propagation in the plates. Figure 2 shows the two different failure modes: rivet shearing, caused by the higher loads (Figure 2a) and crack propagation, after nucleation by fretting, caused by the intermediate and lower loads (Figure 2b). The analysis performed by liquid penetrant testing was on the specimen presenting rivet shearing in order to verify the presence of cracks in the plates. The results can be also seen Figure 2. For the specimen tested with a higher load (5.8 kN), no cracks were found (Figure 2c), showing a pure shearing failure. On the other hand, the specimens tested under 5.15 kN maximum load showed small cracks (Figure 2d), demonstrating crack initiation caused by fretting.

Table 3. Failure modes observed in the fatigue tests.

Specimens	Failure mode
RA 01, 02, 05 and 12	rivet shearing
RA 03, 04, 06, 07, 08, 09, 10, 11 and 13	crack nucleation by fretting and crack propagation in the plates
WA 02, 04, 05, 07, 08, 10, 12, 13, 14 and 16; WB 01, 02, 05, 06, 12, 14 and 15	Shearing fracture
WA 01 and 15; WB 03, 04 and 07	crack propagation in the plates
WB 08 and 10	No failure (run-out)



(a) (b) (c) (d)

Fig. 2. Failure modes observed in the rivet joints during the fatigue tests: (a) rivet shearing; (b) crack propagation perpendicularly to load direction after crack nucleation by fretting; (c) and (d) liquid penetrant test inspection.

The welded joints produced by FSSW also presented two different failure modes (Table 2). Figure 3 depicts both modes; the shearing fracture was the principal mode, observed in almost all specimens, and in some cases the crack propagation occurred perpendicularly to the load in the base material. Shearing fracture mode was originated due to brittleness of the bonded region and can be seen in Figures 3a and b. As cited above, some studies have verified a shearing fracture mode and associated it with either a small resistance in the tensile shear tests or a low cycle in the fatigue tests. However, according to Chang et al [14] and Lin et al [10, 11] studies, the thickness of plates was around 1mm and the aluminium alloys AA 5xxx and AA 6xxx series were studied. As in the present study the plates were 1.6 mm thickness and the alloy was AA2024-T3, more resistant than 5xxx and 6xxx series, deformations in the plates were restricted, thus concentrating the load on the weld spot, and consequently favoring shearing fracture mechanisms.

The failure mode responsible for crack propagation mechanism perpendicularly to the load direction was observed only for low applied loads. Some details are presented in Figures 3d and e. This failure usually displays a transverse crack in the width directions and was also reported [10-12] and always associated with high-cycle loading conditions.

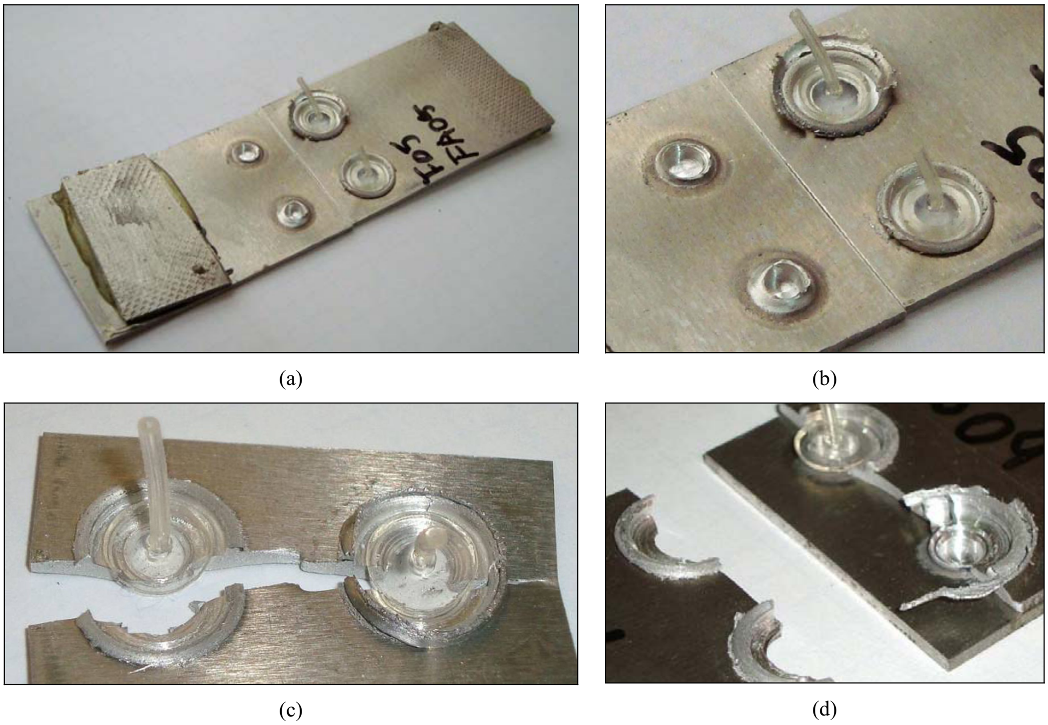


Fig. 3. Failure modes observed in the FSSW welded joints during fatigue tests: (a) and (b) rivet shearing; (c) and (d) crack perpendicular to the load direction.

4. Conclusions

The failure modes of riveted joints observed in the fatigue tests were rivet shearing and crack nucleation by fretting followed by crack propagation in the plates perpendicularly to the load direction. Shearing mechanism was related with high loads and also occurred in tensile specimens. Nucleation by fretting occurred during low to moderate load tests. Among the specimens that failed by rivet shearing, the one tested with higher load (5.8 kN) did not present cracks in an inspection by liquid penetrant test. On the other hand, the specimen tested with 5.15 kN (maximum load) presented some cracks originated by fretting.

Comparing to riveted joints, the FSSW joints exhibited shorter lives in fatigue. The main reasons were the weld heterogeneity (compared with the homogeneous rivet) and the stress concentration at the end of the welds between the plates. However, the FSSW fatigue results were in accordance with the literature, with fatigue lives between 10^4 and 10^5 cycles for loads between 50 and 30% of the maximum tensile shear resistance load respectively.

Regarding failure modes of the welded joints tested under fatigue, two types were observed, i.e. shearing fracture and crack propagation in the plates perpendicularly to the load direction. The first mode was more frequent and was the same presented in the tensile shearing tests, occurring for higher loads. The second mode, with transverse cracks, was observed only in some high-cycles tests, with low load applied.

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