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Fatigue behavior throughout friction stir processing joints in AA2024-T3

Atheer Najm Abed[1], Dr. Ghanim Sh. Sadiq[2]
Mechanical engineering department, Alnahrian University, Iraq
Mechanical engineering department, Alnahrian University, Iraq

Abstract: In this work the 2024-T3 aluminum alloys of 3mm thickness were butt joined by using FSW and FSP. Two different process parameters have been selected which are: rotational speed of 1400 and 2000 RPM and welding speed of 20,35 and 50 mm/min. The tool that used for both FSW and FSP has a cylindrical profile. thirteen cases of welding and base metal have been testing under tensile test, which led to select the optimal welding process of FSP with rotating speed of 1400 RPM and welding speed of 35 mm/min. The efficiency of tensile strength reaches to 92% for FSP and 89.02% for FSW compare to the base metal. Two tests have been done for the fatigue which are the constant and variable amplitudes on the specimen of FSP 1400 RPM and 35mm/min. the endurance limit for the base metal was 54 at 10^7 with R^2 of 0.98, while the selected FSP specimen has an endurance limit it 51at 10^7 with R^2 of 0.97. Variable amplitude of L-H-L and H-L-H have been applied on the base metal and the selected FSP specimen. Where the low stress was 200 MPa and the high stress was 300 MPa. The linear method achieved the highest value of 1.279 with base metal with load type of (H-L-H), however the non-linear method achieved better results with 1.267 of base metal with load type of (H-L-H), and 1.005 with load type of (L-H-L) for FSP specimen.

Keywords*:* Fatigue behavior-friction stir processing - Aluminum Alloy 2024-T3

1. Introduction

Friction stir welding and friction stir processing are a material joining mechanism in which two or more metal work pieces are connected by a spinning tool that traverses around the weld, causing friction heating and mixing of material in the plastic state. They are regarded as the most notable advancement in metal joining in a decade [1].Friction Stir Welding(FSW) is a solid-state welding technology invented by The Welding Institute(TWI), UK, in 1991. As shown in Table (1). The rotation speed and welding speed of the stirring tool are the main factors affecting fatigue Performance of FSW joints. the FSW tool rotates at high speed and plunges into the work piece. The Heat generated by friction and material deformation softens the surrounding material, when the tool moves along the weld direction, the material is stirred and forced from advancing side to retreating side to fill the space behind the tool[2], consequently forming the weld. Compared with conventional fusion welding technologies, FSW can avoid defects such as porosity, lack of penetration, hot cracking, and distortion

Table (1): Al 2024-T3 alloy Chemical composition

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Standard	0.31	0.248	4.03	0.58	1.57	0.1	0.25	0.15

In this paper, Aluminum pieces were welded by FSW (one pass) and FSP (two pass), with different rotational speed and welding speed, were selected, tensile samples were taken, tested, and the best results were selected for Fatigue testing to the samples of aluminum welded by the friction stir welding and comparing them with the base metal (without welding).Metal fatigue includes the start and cracks development below the effect of cyclic stresses prompted by reoccurred use of service loads. Residual stresses remaining from manufacture further play a significant part in increasing metal fatigue [3].Metal fatigue takes on greater significance with improving the level of yield strength due to greater strength alloys seldom, and give excellent fatigue crack growth resistance, compared to materials of lower strength, yet are predicted to provide higher working stresses. The outcome of this fact is an inclination to overwork high strength alloys in fatigue conditions, therefore expressing fatigue breakdown

2. Experimental

2.1 Material

The aluminum alloy 2024-T3 was investigated. Chemical composition is given in Table 1. The material thick 3mm was produced as extruded flat profile. Alloy 2024 is a high strength, alloy that contains copper The copper provides substantial increases in strength and facilitates precipitation hardening [4]. The introduction of copper to aluminum can also reduce ductility and corrosion resistance. Aluminum pieces with dimensions of 100 * 200mm were cut by water jet

1.2 Welding

The FS welds were produced by the welding process curried out by using the HARTFORD CNC milling machine. The parts were joined with a welding speed of (20, 35, and 50) mm/min and the rotation speed was 1400 &2000 RPM. In this paper two parameters which are the rotating speed (1400 and 2000 RPM) and welding speed (20, 35, and 50 mm/min) are utilized to study each one influence on the welding quality through microstructural and mechanical properties of the cross section of joint line. Table (2) shows the given names for each specimen at the selected welding type, rotating speed and welding speed

Table (2): Specimen's classification

Case	Symbol	Welding type	Rotating speed (RPM)	Welding speed (mm/min)
B.M	Base metal	N/a	N/a	N/a
Case 2	FSW	Friction stir welding	1400	20
Case 3	FSW	Friction stir welding	1400	35
Case 4	FSW	Friction stir welding	1400	50
Case 5	FSW	Friction stir welding	2000	20
Case 6	FSW	Friction stir welding	2000	35
Case 7	FSW	Friction stir welding	2000	50
Case 8	FSP	Friction stir processing	1400	20
Case 9	FSP	Friction stir processing	1400	35
Case 10	FSP	Friction stir processing	1400	50
Case 11	FSP	Friction stir processing	2000	20
Case 12	FSP	Friction stir processing	2000	35
Case 13	FSP	Friction stir processing	2000	50

2.3 Tensile Test

A specimen for tensile test was done using a tensile testing instrument, as presented in Figure (1), at a speed of 5 mm /min to test specimens of 2024-T3 aluminum alloy were set following the ASTM E8 standard [5].

Figure (1): tensile tester

2.4 Fatigue tests

The fatigue tests were performed in accord with ASTM The traditional Howler fatigue test uses HI-TECH alternating bending instrument the load at the end this instrument imposes a known bending moment as show in figure (2)

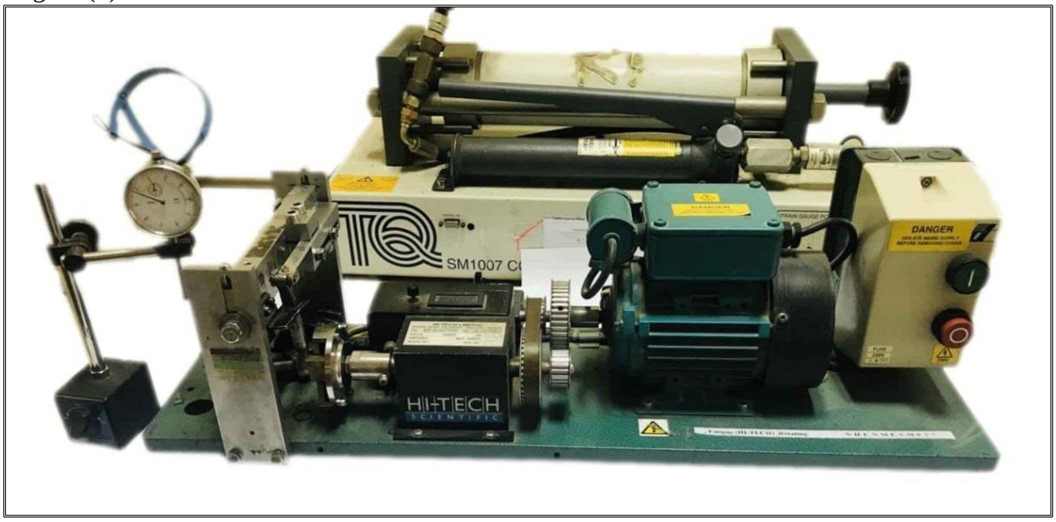

Figure (2): Fatigue alternating bending test device

That results in a sinusoidal varying stress as the cantilever rotates with a stress ratio of *R*= -1. The minimum stress was (100 MPa) and the maximum stress was set at 400 MPa. in this paper we study the constant load and variable load. The specimen dimension was 100mm,10 mm ,length and width respectively As shown in Figure 3

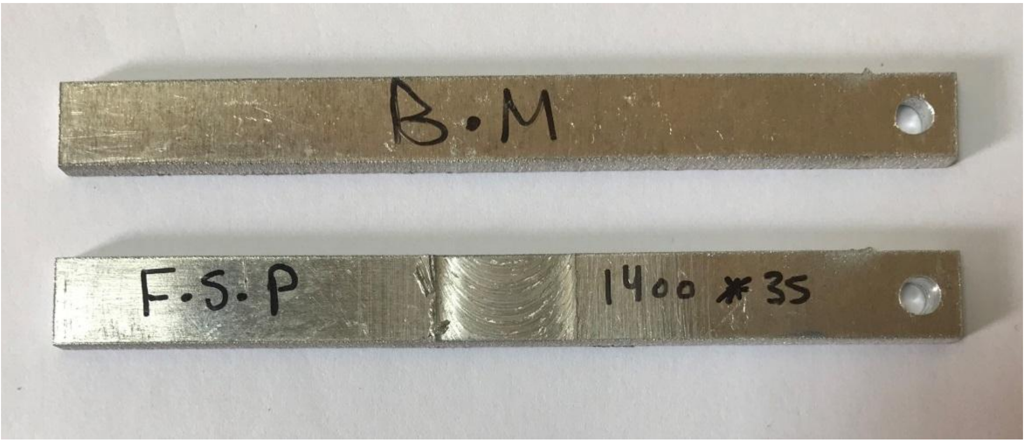

Figure (3): fatigue testing specimens

2.3.1 Constant fatigue test

The fatigue test is considered one of the most important mechanical tests to know the behavior of the metal when it is exposed to loads [6]. During this research, the sample that was welded by friction stir processing for 1400 rotation speed and 35 mm/min wielding speed will be exposed to various variable loads and compared with samples of the original metal. The fatigue test is a cyclic bending loading procedure with R=-1 [7]. The purpose of the test is to generate *S-N* data (stress vs. number of cycles) for metal used.

2.3.2 Variable fatigue test

More complicated sequences of amplitude are required in order to simulate the stresses to which a specimen is subjected in actual service .variable fatigue test type (three-step) was done until failure on smooth surface specimens of base Al 2024-t3, and FS processing .Two samples of each type were tested under (low-High- low), (High-low- High) loading to get the variable results.

3. Results and discussions

3.1 Tensile Results

Figure (4) to (5) present the tensile test results for both FSW and FSP at rotating speeds of 1400 and 2000 RPM and welding speed of 20, 35, and 50 mm/min respectively. The presented results in the tensile testing were the average of three identical specimens, which is done to obtain more reliable data from the testing and minimize the chances of error in the reading. The base metal stress was 455.2 Mpa. However, the FSW maximum stress 411.3 Mpa was at case 2 of 1400 RPM and welding speed of 35 mm/min. While the FSP joint maximum stress was 421.7 MPa with efficiency of 92.64%, at similar welding conditions for the FSW, case 2. The effect of welding speed tensile strength of FSW is directly proportional to the feed / welding speed [8]

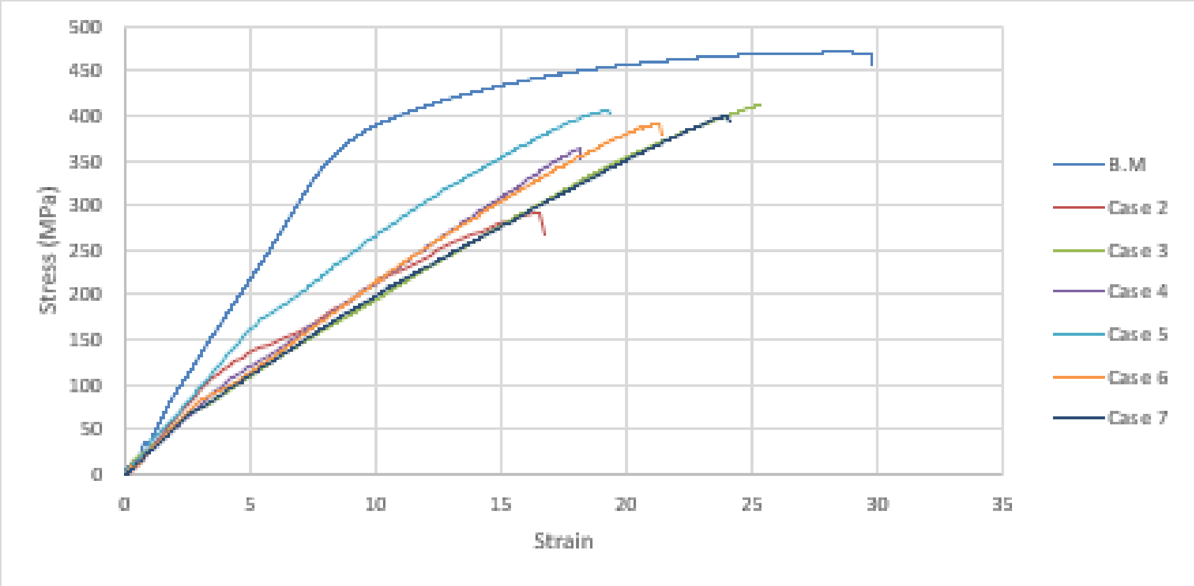

Figure (4): FSW tensile results of specimens

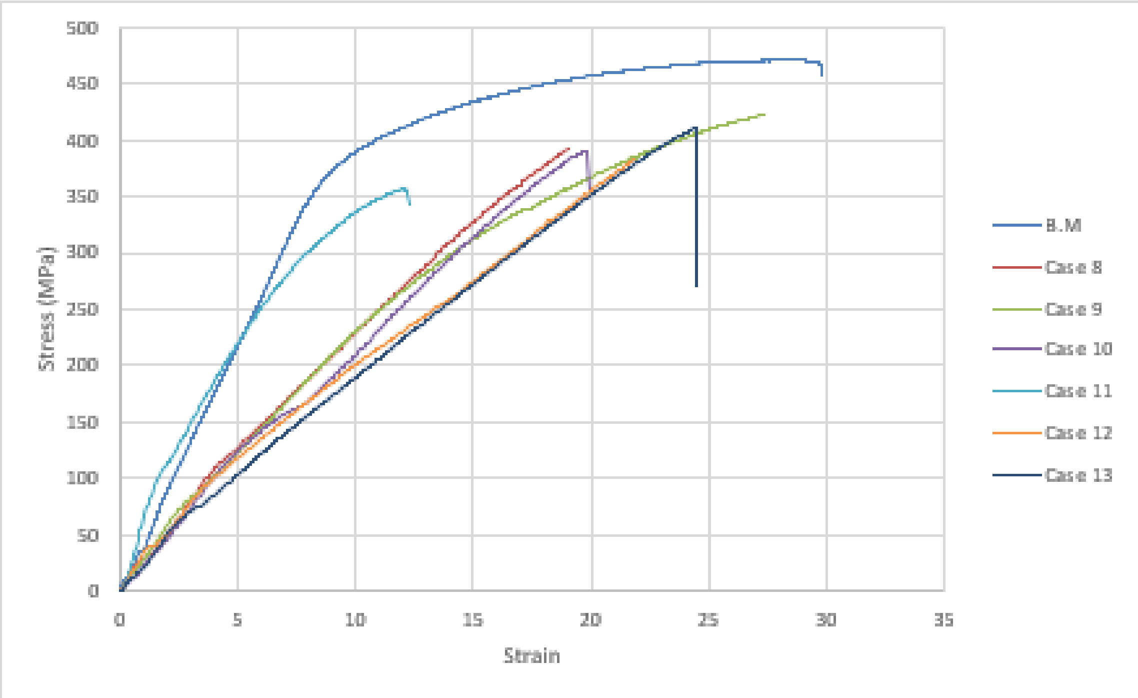

Figure (5): FSP tensile results of specimens

3.2 constant fatigue results

Fatigue analysis are normally based on the results obtained from constant amplitude

Table (3): constant amplitude data

#	Stress (Mpa)	Base metal			FSP(1400*35)		
		Nf1	**Nf2**	**Nf , Average**	**Nf1**	**Nf2**	**Nf , Average**
1	100	1262481	1244373	1253427	1113064	1113064	1102718
2	150	524395	508397	516396	382856	373738	378297
3	200	208403	199025	203714	168780	149012	158896
4	250	172474	170212	171343	119362	107274	113318
5	300	65563	62703	64133	46789	45923	46356
6	350	52954	51640	52297	41535	36803	39169
7	400	37451	33713	35582	23915	22845	23180

The results of fatigue tests for base material and FSP specimens were presented in Figure (6). The resulted data have been curve fitted with power line model. Approximately the suggested mathematical model gives a good fitting.

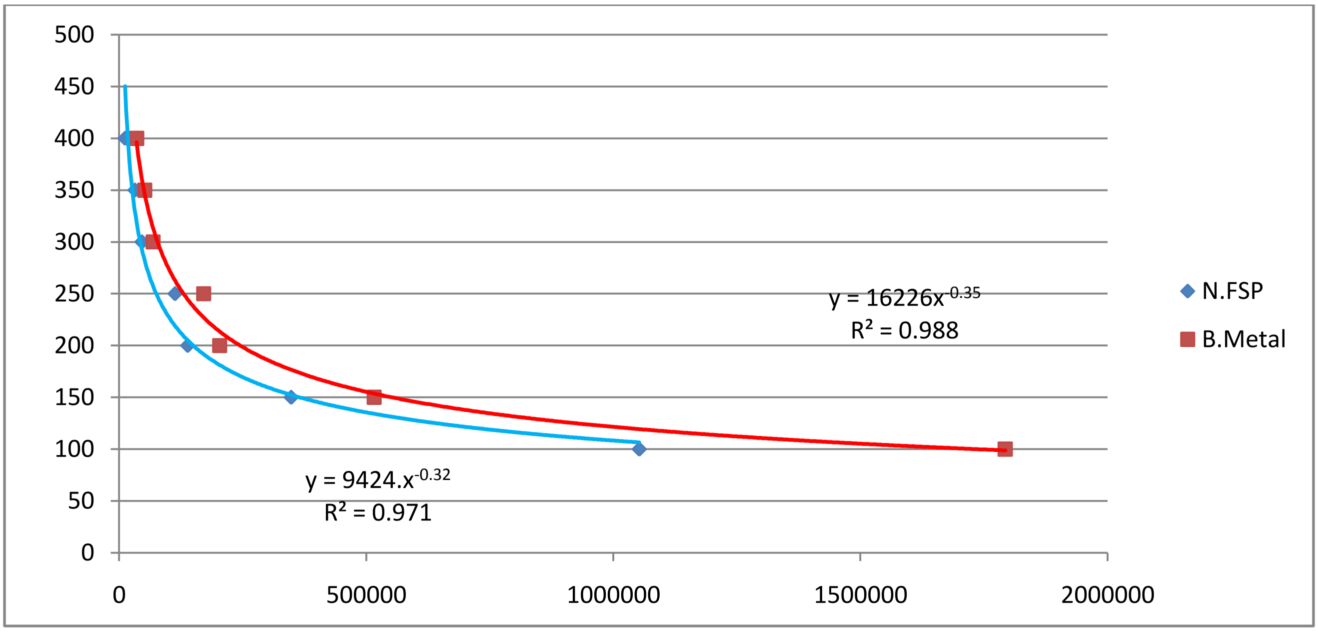

Figure (6): S-N curves of fatigue life for base metal and FSP

3.3 Variable Amplitude Results

Table (4)present the obtained data for variable amplitude where the base metal and FSP undergo this fatigue test. The base metal and FSP specimens were exposed to variable load of three steps type (low-high-low) and (high-low-high) for stress of 200 MPa and 300 MPa for each cyclic load

Table (4): Variable amplitude data

NO	Lode	Stress1 Mpa	n1	Stress2 Mpa	n2	Stress3 Mpa	n3	NT	Nf.exp	NT/Nf.exp
B.M										
1	**L-H-L**	**200**	**5000**	**300**	**5000**	**200**	**176398**	**186398**	**203714**	**0.914**
2	**H-L-H**	**300**	**5000**	**200**	**5000**	**300**	**75494**	**85494**	**64133**	**1.333**
FSP										
3	**L-H-L**	**200**	**5000**	**300**	**5000**	**200**	**118335**	**128335**	**158896**	**0.807**
4	**H-L-H**	**300**	**5000**	**200**	**5000**	**300**	**28816**	**38816**	**46356**	**0.836**

3.4 Accumulative Damage

To study the accumulative damage for base metal and FSP (rotating speed: 1400, welding speed: 35 mm/min). Three step loads have been applied to each specimen for the base metal and processed one. For the low load the value of stress was 200 MPa and for the high load the value was 300 MPa. The pattern of the applied loads was as (LOW - HIGH - LOW) and (HIGH - LOW- HIGH). The cumulative damage models that have utilized in this work are linear rule (Palmgren - Miner), and non-linear damage model. Table (5) present the obtained results for the accumulative damage models. where it can be noted that both models have achieved good results. However, base metal shows good outcome for linear model and under H-L-H load pattern, while the non-linear model for both base metal and FSP specimens have higher lifespan except for FSP specimen under (HIGH - LOW- HIGH) load.

Table (5): Accumulative damage of base metal and FSP for (AA2024-T3)

Type of specimen	Type load	Linear Rule	Non-Linear Rule
B.M	**L-H-L**	**0.968**	**1.065**
B.M	**H-L-H**	**1.279**	**1.267**
FSP	**L-H-L**	**0.884**	**1.005**
FSP	**H-L-H**	**0.970**	**0.966**

4. Conclusion

Aluminum alloy of 2024-T3 has a special importance in many industries such as aircraft, gears, and defense applications. This work focused on comparing the FSW and FSP welding processes to obtain the best rotating and welding speeds that can produce a welded sheets of 2024-T3 to withstand harsh operating conditions. Two rotating speeds of 1400 and 2000 RPM along with three welding speeds of 20, 35, and 50 mm/min have been utilized in both FSW and FSP. The following points summarize the obtained results from this work.

1. Welding of 2024-T3 by friction stir processing is better than friction stir welding at the same rotating speed and welding speed.
2. The best efficiency of joints of the used parameters of FSP AA 2024-T3 is found at 35 mm/min weld speed and 1400 RPM rotation speed, it reaches efficiency of 92.64 % of the tensile stress of the base metal for FSP

3. FSP at 1400 RPM-35mm/min (case 9) shown to be the optimal speed for welding of 2024-T3, based on the done tests for this case specimen
4. The fatigue results from S-N carve shows the Endurance limit for FSP was 51 Mpa , while the base metal reached to 54 Mpa
5. The R2 for case 9 fitting was 97% and for the base metal was 98%
6. Accumulative fatigue for FSP specimen under load type (L-H-L) for non-linear model has 1.005 while for base metal under similar load pattern was 1.065
7. Linear damage model was less accurate for both base metal and FSP under different load pattern

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