Multi Objective Process Parameters Optimization of Friction Stir Welding using NSGA – II

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Abstract

Age hardenable aluminum alloys such as AA2024 and AA6061 are extensively usd in automotive, aircraft and marine industries because of its high strength to weight ratio and good ductility. When compared to fusion welding techniques Friction Stir Welding (FSW) is a promising technique to improve the quality of the weld joint. FSW process parameters such as tool rotational speed (N), welding speed (F), axial load (P) and tool pin profiles (Cylindrical, Square and Taper) have crucial effects on the mechanical properties of FS welded joints significantly. The mathematical model was developed for the responses namely Ultimate Tensile Strength (UTS) and Tensile Elongation (TE) using Response Surface Method (RSM) and the developed mathematical model was effectively utilized to optimize the FS welded process parameters using non-dominated sorting genetic algorithm-II (NSGA-II). The maximized tensile properties of FS welded age hardenable aluminum alloys were obtained nearly 143.3 N/mm^2 with its corresponding tensile elongation of 12.53%. It is concluded that, the NSGA – II is very useful in optimizing the process parameters of FS Welding and improving the quality of the weld joint.

Keyword: Friction stir welding, NSGA, tensile, elongation, micro structure, response surface

1. Introduction

In the present scenario light weight structure applications are more demanding in nuclear, aircraft and marine industries to improve fuel economy and payload capability. Friction stir welding (FSW) is a modern solid-state welding is used for joining many light-weight alloys such as aluminum alloys, magnesium-based alloys. In FSW, a rotating tool comprising of a pin and a shoulder is squeezed against the synchronized ends of two metal plates to be welded, while traversing along the weld line. A significant advantage in FSW is, heat transfer between the plates is accomplished by the deformation of the two plates and the tool therefore no melting occurs therefore weld line is made in solid state. In recent years joining of age hardenable aluminum alloys is an intriguing topic in the welding research. Due to inherent weld qualities such as porosity and sensitive to cracking, age hardenable aluminum alloys are not suitable to weld using conventional welding technique hence; these materials are categorized by difficult to weld metals. Owing to its excellent mechanical and metallurgical properties such as fine recrystalized grains, and reduction or absence of superficial and internal flaw on the weld zone etc., Weld quality is affected by many process parameters in FSW that leads imperfections like voids, pinholes during the welding process (1). It is difficult to select appropriate process parameters even a skilled labor to obtain optimum weld quality. Therefore, it is necessary to obtain a mathematical relationship between the process parameters to optimize the weld quality. In the past 5 years, evolutionary algorithms such as artificial neural network (2), genetic algorithm (3-5), simulated annealing algorithm (6), particle swarm optimization, and Non Dominated Sorting Genetic Algorithm (NSGA – II) have become popular in finding the suitable process parameters, especially if the process is too complex.

Among the various popular evolutionary algorithms, Non-Dominated Sorting Genetic Algorithm - II (NSGA - II) is extensively adopted in all manufacturing processes such as machining, forming and welding as an effective approach to improve the quality of the product. NSGA - II searches a whole design space for global optimum operation by various design points using random

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genetic operations (7). The conventional NSGA has been generally criticized for its lack of elitism and need for specifying the sharing parameters. But the modified NSGA – II which has a better sorting algorithm and no sharing parameter needs to be specify sharing parameter. Despite the fact that the NSGA - II offers numerous advantages on manufacturing processes, very limited numbers of investigations were carried out so far on FSW of age hardenable alloys using NSGA - II. For instance, Bandaru et al. (8) proposed an investigation to minimize the temperature difference between the leading edge of the FSW tool probe and the work piece material using NSGA - II. Akabri et al (9) optimized the process parameters of A356 composite fabricated by FSP using TOPSIS and NSGA – II. Residual stress across the weld position on age hardenable aluminum alloys was estimated by Hidalgo et al (10) using NSGA – II algorithm. Though numerous attempts have been made to optimize the friction stir welding process parameters for improving the ultimate tensile strength and tensile elongation, an attempt of NSGA – II to find the optimal friction stir welding process parameters for improving the ultimate tensile strength and tensile elongation of AA2024 – AA6061 age hardenable aluminum alloys are very rare. Hence, in the present investigation the aluminum alloys AA2024 – AA6061 friction stir weld joints are considered to optimize the process parameters using NSGA – II.

2. Experimental setup

The schematic arrangement of FSW setup of joining age hardenable aluminum alloys and the fabricated FSW tools are presented in Figure 1. Age hardenable aluminum alloys of AA2024 and AA6061 were cut from 6.25mm sheet with dimensions of 300 mm x 150 mm by computerized friction stir welding machine to fabricate the dissimilar weld joints of AA2024-AA6061 aluminum alloys.

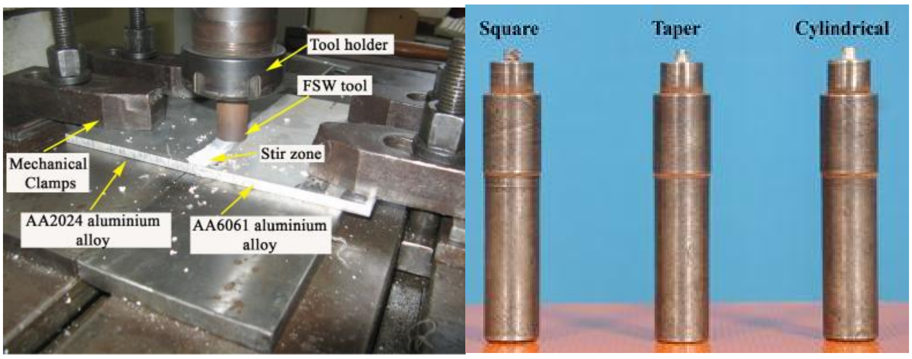

Figure 1. FSW Setup and fabricated tools

Four important FS welding process parameters namely tool rotational speed (N), welding speed (F), axial force (P) and pin profiles (PP) such as cylindrical (1), Square (2) and taper (3) is considered. A mechanical clamping device was used to hold the plates in position. H13 hot work steel was used to fabricate the rotating tools. Due to pin rotation the friction created heat in the pieces and turned the intended area for welding into plastic state. The use of protection gas during welding was not required, since there was no melting during this process (11). The FS welding process parameters and their range is presented in Table 1. 3 levels, 4 factors RSM based BBD design was used to design the experiment. Therefore, totally 31 experiments were conducted as per the design matrix.

Table 1. FS welding parameters and their range

FSW Parameters	Range
Tool rotational speed, N (rpm)	1700 – 1900
Welding speed, F (mm/min)	30 – 90
Axial force, P (kN)	3 – 9
Pin Profiles (PP)	Cylindrical (1), Square (2) and Taper (3)

All the fabricated specimens were subjected to ultimate tensile strength and tensile elongation as per ASTM E384. The tensile specimens were cut longitudinal direction along the stirred line. The fabricated FS welded samples as per the design matrix is presented in Figure 2. Scanning electron microscope (SEM) was used to analyze the microstructural properties of FS welds. Few defects were absorbed on the stir zone and are presented visually in Figure 3. Two responses namely ultimate tensile strength (UTS) and tensile elongation (TE) are considered for optimization. The design matrix and their corresponding results were presented in Table 2. When comparing to other pin profiles, square pins playing a significant role in yielding the maximum tensile strength and tensile elongation of AA2024 and AA6061 age hardenable aluminum alloys.

Figure 2. Fabricated FS weld samples

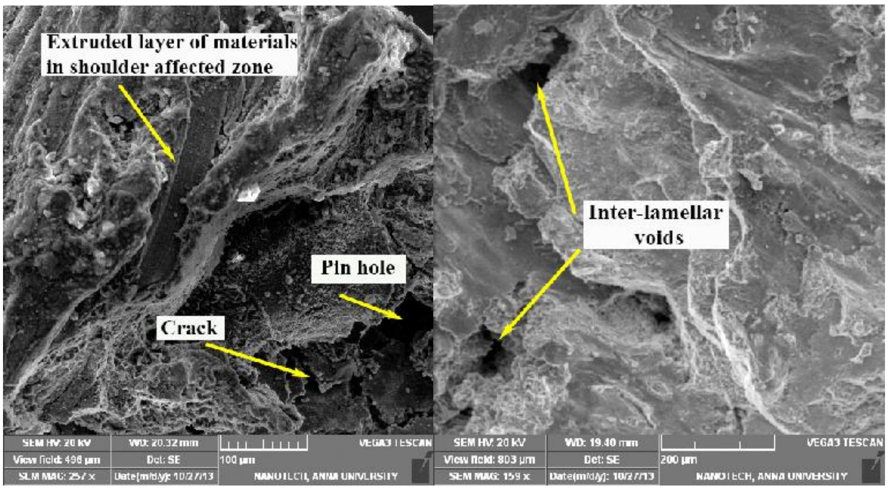

Figure 3. FS welding defects

Table 2. Design matrix and results

Std	Run	A:Rotational speed (RPM)	B:Welding speed (mm/min)	C:Axial load (kN)	D:Pin Profile	Ultimate Tensile Strength (UTS) (MPa)	Tensile Elongation (TE) (%)
1	7	1500	30	6	2	108.31	10.97
2	8	1900	30	6	2	109.33	9.23
3	11	1500	90	6	2	109.32	11.45
4	5	1900	90	6	2	101.06	9.45
5	25	1700	60	3	1	122.25	12.38
6	3	1700	60	9	1	127.09	10.16
7	4	1700	60	3	3	117.64	11.37

8	22	1700	60	9	3	124.31	9.72
9	18	1500	60	6	1	122.34	11.26
10	28	1900	60	6	1	119.06	10.54
11	6	1500	60	6	3	120.21	11.1
12	30	1900	60	6	3	115.37	9.11
13	21	1700	30	3	2	107.34	11.56
14	14	1700	90	3	2	106.13	11.77
15	23	1700	30	9	2	116.31	10.03
16	17	1700	90	9	2	112.31	10.49
17	20	1500	60	3	2	118.52	12.28
18	29	1900	60	3	2	115.98	10.12
19	19	1500	60	9	2	122.66	10.26
20	27	1900	60	9	2	124.22	9.37
21	31	1700	30	6	1	115.32	10.67
22	16	1700	90	6	1	104.34	11.67
23	26	1700	30	6	3	110.27	9.92
24	13	1700	90	6	3	108.31	10.89
25	24	1700	60	6	2	138.4	12.11
26	15	1700	60	6	2	143.64	12.25
27	2	1700	60	6	2	139.21	12.12
28	12	1700	60	6	2	139.28	12.48
29	1	1700	60	6	2	139.91	12.45
30	10	1700	60	6	2	141.34	12.38
31	9	1700	60	6	2	143.3	12.53

3. Multi objective optimization using NSGA

The main objective of the present investigation is to maximize the tensile properties such as ultimate tensile strength and tensile elongation by optimizing the FS welding process parameters. Therefore, it can be considered as multi-objective optimization problem. The Matlab code was developed using the version R2010b. The developed mathematic model of multi-objective problem can be developed as below:

Ultimate tensile strength (UTS) = -(-902.25563+1.03486*X(1)+3.33452*X(2)+12.33048*X(3)+ 32.16226*X(4)-0.000386*X(1)*X(2)+0.075167*X(2)*X(4)-0.000299*X(1)^2-0.024151*X(2)^2-0.93717*X(3)^2-9.46577*X(4)^2);
Tensile Elongation (TE) = -(-73.10948+0.096367*X(1)+0.11732*X(2)-0.31669*X(3)+5.21411*X(4)+0.000529167*X(1)*X(3)-0.0015875*X(1)*X(4)-0.000029507*X(1)^2-0.000903*X(2)^2-0.070450*X(3)^2 -0.72405*X(4)^2);

Subject to,
1700rpm ≤ Rotational speed (N) ≤ 1900
30 ≤ Welding speed (F) ≤ 90
3 ≤ Axial force (P) ≤ 9
1 ≤ Tool pin ≤ 3 where 1 = Cylindrical pin, 2 = Square Pin and 3 = Taper Pin

Since there are trade-offs among these two objectives, the optimization problem in equation (1) generally has a set of optimum solutions. These solutions are optimum in the Pareto sense, that is, there is no optimum better than other designs in all objectives. NSGA-II is implemented to solve the

FS welding process parameters optimization problem and obtain the Pareto optimal front. The settings for the NSGA-II in this optimization problem are presented in Table 3.

Table 3. NSGA input parameters

Parameters	Value
Population size	100
Mutation fraction	0.2
Maximum iterations	500
Pareto fraction	0.4
Elite count	2
Function tolerance	10E-06
Crossover function	0.8
Scaling fitness function	Rank

4. Optimization results

Figure.4 show plots the obtained Pareto-optimal front for Ultimate Tensile Strength and Tensile Elongation. Each point in Figure illustrates a specific optimal solution, whose corresponding process parameters can be adopted according to the requirements of the design makers. The obtained NSGA solutions are presented in Table. It can be concluded from Figure that all optima are non-inferior with each other because there are trade-offs among the ultimate tensile strength and tensile elongation, e.g., the maximum ultimate tensile strength obtained is nearly 143.3 N/mm^2 with its corresponding tensile elongation of 12.53%.

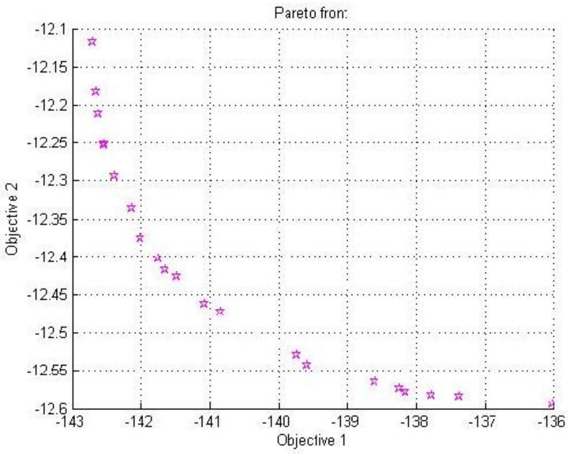

Figure 4. Pareto Optimal plot

Table 4. Pareto Optimal solutions

Run	Ultimate tensile strength (Mpa)	Tensile elongation (%)	Rotational speed (rpm)	Welding speed (mm/min)	Axial load (kN)	Pin profile
1	-133.47	-12.82	1626.34	65.20	3.86	1.82
2	-134.37	-12.82	1630.98	63.85	3.93	1.82
3	-142.79	-12.18	1692.15	59.25	6.59	1.94
4	-133.47	-12.82	1626.34	65.20	3.86	1.82
5	-139.58	-12.71	1643.75	61.74	5.04	1.84
6	-141.67	-12.54	1666.21	61.36	5.70	1.89

7	**-142.70**	**-12.30**	**1688.76**	**59.27**	**6.30**	**1.90**
8	**-142.27**	**-12.41**	**1669.84**	**61.27**	**6.15**	**1.87**
9	**-142.40**	**-12.38**	**1663.52**	**59.87**	**6.26**	**1.88**
10	-136.47	-12.80	1639.58	64.16	4.34	1.83
11	**-142.04**	**-12.49**	**1664.70**	**59.62**	**5.85**	**1.90**
12	-136.98	-12.79	1636.73	63.66	4.46	1.82
13	-139.18	-12.72	1655.52	62.39	4.82	1.92
14	-140.36	-12.67	1652.99	61.05	5.21	1.84
15	-135.98	-12.80	1634.61	64.29	4.25	1.88
16	-141.75	-12.52	1672.45	61.62	5.73	1.87
17	-139.70	-12.70	1640.17	62.38	5.13	1.89
18	**-142.62**	**-12.31**	**1683.17**	**60.24**	**6.36**	**1.87**
19	-138.63	-12.74	1659.14	62.31	4.66	1.86
20	**-142.18**	**-12.44**	**1668.58**	**61.32**	**6.06**	**1.89**
21	-138.98	-12.73	1645.32	63.63	4.95	1.84

Six solutions in the Pareto-optimal front were selected randomly (based on obtained maximum tensile strength and 'tensile elongation) (run no: 7,8,9,11,18, & 20) to verify the effectiveness of the optimal results. The fabricated weld samples based on confirmation experiments is presented in Figure 5. The confirmation experiment results are compared with optimization results. The obtained confirmation results and optimization results are plotted in Table 5.

Table 5. Confirmation experiment results

Experimenal run	Rotational speed (N), rpm	Welding speed (F), mm/min	Axial force (F), kN	Pin profile	NSGA results		Confirmation results	
					UTS (N/mm^2)	TE (%)	UTS (N/mm^2)	TE (%)
7	1688.76	59.27	6.3	1.9	142.7	12.3	143.14	12.54
8	1669.84	61.27	6.15	1.87	142.27	12.41	141.45	11.58
9	1663.52	59.87	6.26	1.88	142.4	12.38	141.35	12.11
11	1664.7	59.62	5.85	1.9	142.04	12.49	142.65	12.14
18	1683.17	60.24	6.36	1.87	142.62	12.31	143.65	12.65
20	1668.58	61.32	6.06	1.89	142.18	12.44	140.15	11.64

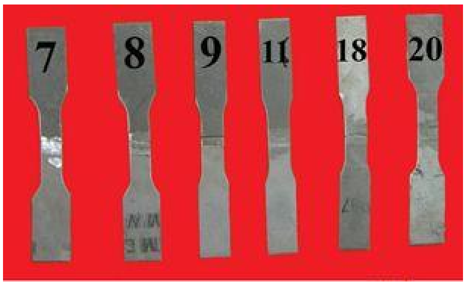

Figure 5. Confirmation experiment samples

The confirmation experiments indicated that the prediction accuracy of proposed NSGA – II optimization approach can meet the requirement of FS welding of AA2024 and AA6061 age hardenalbe aluminum alloys.

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5. Conclusion

Non-Sorted Genetic Algorithm (NSGA – II) optimization technique is proposed to obtain the optimal process parameters in FS welding of AA2024 and AA6061 age hardenalbe aluminum alloys. Following conclusions can be drawn from the above investigation:

1. The tensile properties of AA 2024 and AA6061 age hardenable aluminum alloys have greatly increased by the optimizing the FS welding process parameters namely tool rotational speed (N), welding speed (F), axial force (P) and pin profiles (PP) such as cylindrical, square and taper.
2. Square pin profile playing a significant role and yielded a maximum tensile strength and tensile elongation when fabricated AA2024 and AA6061 age hardenable aluminum alloys.
3. Confirmation experiments is in good agreement with optimization results. NSGA-II was proved to be feasible and would be useful to guide FS welding of age hardenable aluminum alloys.

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