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Tensile strength prediction of aluminium alloys welded by FSW using response surface methodology – Comparative review

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ABSTRACT

Friction Stir Welding (FSW) process is an invented welding technique where a non-consumable tool uses to join two surfaces. Welding speed, tool rotational speed, axial load, and geometry of the tool consider as key variables in determining the joint's strength in this process. Response Surface Methodology (RSM) is one of the familiar techniques used to optimize the welding parameters. Herein, a comprehensive literature review of using RSM for modelling and optimizing the joint strength has been introduced. This study also examines the presented empirical equations and compare the optimum condition results for the similar and dissimilar alloys. The review indicates that the central composite design matrix with three or four factors is the main method used for RSM. Furthermore, most studies are focused on alloys 1xxx, 6xxx and 2xxx with few studies on 5xxx and 7xxx while there are very limited studies on 3xxx, 4xxx. The optimum tensile strength varies from (73–105) MPa for Al 1xxx series, (219–360) MPa for 2xxx series, (255–294) MPa for 5xxx series, (104–288) MPa for 6xxx series and (319–377) MPa for 7xxx series depending on process parameters.

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1. Introduction

Friction stir welding (FSW) process is a creative solid-state joining technology introduced since more than two decades at The Welding Institute [1]. It is noted that the FSW process offers several benefits as compared to many processes of fusion welding, it is classified as a creating solid state joining technology where the welded metals do not melt and recast [2]. FSW process uses a non-consumable rotational tool to weld two sheets depending on the generated heat of friction contact [3]. Furthermore, special surface treatment does not require after the FSW process, no shielding gas and it do not leave waste, porosity, or fumes so that is considered as economical and very environmentally friendly [4]. On the other hand, the exit hole which is considered the main disadvantage of FSW [5]. Later, there are several updates occurred for friction stir welding such as pulsed FSW [6], electric assisted FSW [7], self-reacting (SR-FSW) [8], friction stir spot welding (FSSW) [9] and friction stir processing (FSP) [10].

Most of the FSW researchers use a milling machine where the rotating tool is having a special shape; upper cylindrical part (shoulder) and lower part (pin) as indicated in Fig. 1. The shoulder is a cylindrical shape part which is forced against the welding specimen, while the pin is having different shapes uses to force between the two plates depending on the milling machine axial force. The friction force between the plates and the rotating tool is quite enough to generate the required heat for decreasing the resistance of plastic deformation of the metal or polymers. The milling machine welding speed moves the softened material which leads to the required solid-state weld forming. Aerospace industries applications such applied to weld wings, fuselages, cryogenic fuel tanks consider the main applications of FSW. Furthermore, it is used in railways, trams, and other transportation applications [11].

It is essential to optimize the welding parameters to get the greatest hardness, joint strength, and other mechanical properties. Spindle rotational speed (N), axial load (F), traverse speed (S), dwelling time, and tool geometry are the formal FSW process parameters. These parameters are independent, and the values of tensile strength can be changed according to any change of them as shown in Fig. 2. There are several techniques are used before

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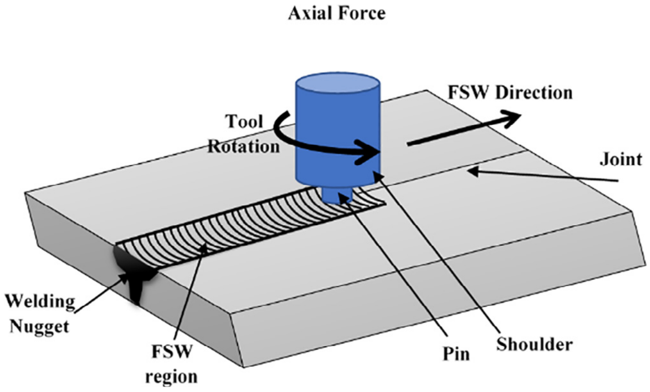

Fig. 1. FSW process schematic drawing.

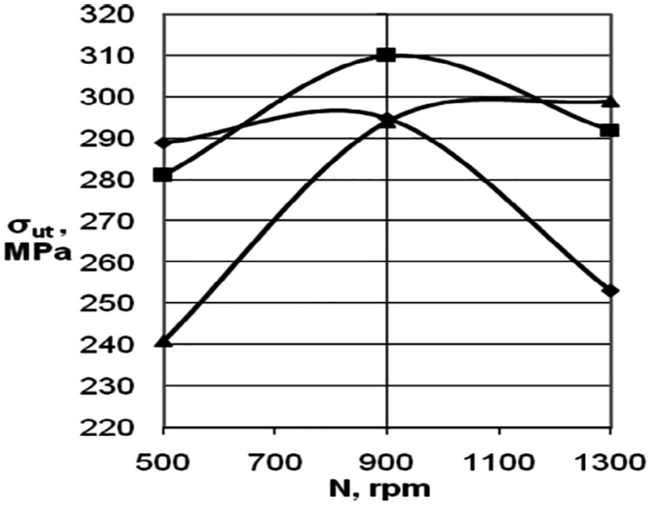

Fig. 2. Rotational speed and traverse speed effect (S = 30 mm/min (■); S = 50 mm/min (◆); S = 70 mm/min (▲) [12]

to optimize the FSW parameters such Taguchi method [12], neural network [13], fuzzy logic [14] and response surface methodology base on ANOVA. In this article, an attempt of reviewing RSM mathematical models which are published to predict FSW joint strength.

2. Response surface methodology

In 1951, Box and Wilson introduced Response Surface Methodology (RSM) as statistical as well as mathematical technique. RSM is a good tool for analysing and optimizing problems where the dependent variable is controlled by more than one independent variables [15].

$$Y = \varnothing(x_1, x_2, \cdots .x_k) \pm e_r \tag{1}$$

The response surface Y which specified by the equation:

$$Y = b_o + \sum b_i x_i + \sum b_{ij} x_i + \sum b_{ij} x_i x_j + e \tag{2}$$

Sometimes, the input variables in the response surface methodology are called independent variables, while the output called a response function. Response Surface Methodology is an important technique of surrogated modelling widely used by researchers, therefore techniques and concepts of RSM have been extensively applied in many branches of engineering, especially in the manufacturing, mechanical, chemical, geotechnical areas. Also, its applications expanded to include more fields such as structural health monitoring [16]. In the last decade, many researchers have used RSM for predicting an empirical relationship of tensile strength to optimize the FSW process. In these studies, the tensile strength is considered as a response function of several parameters such as welding speed, axial load, spindle rotational speed and dwelling time besides tool geometry parameters such as tilt angle, shoulder and/or pin diameter.

3. Results and discussions

A range of practically most classes of wrought compositions aluminum alloys had been successfully friction stir welded such as Al + 99% (1xxx), Al-Cu (2xxx), Al-Mg (5xxx), Al-Mg-Si (6xxx) and Al-Zn-Mg-Cu (7xxx) while there were very limited studies on Al-Mn (3xxx) and Al-Si (4xxx), therefore, 3xxx and 4xxx alloys did not covered in this review. For casting compositions aluminum alloys, the series 3xx.x (silicon added copper and/or magnesium) had been successfully friction stir welded especially A356, 319, and A390 alloys [17]. In addition to Aluminum alloys, FSW studies expanded to ferrous alloys, nickel alloys, copper alloys and magnesium alloys.

3.1. Aluminum 1xxx series

All studies on 1xxx Aluminum Series focused on AA1100 (99+% Al). AA1100 considered as good weldablity low cost pure aluminum alloy. The typical tensile strength of representative non-heat-treatable AA1100 alloys varied from 90 MPa to 165 MPa depending upon the alloy's temper [18].

The ultimate tensile strength (UTS) of AA1100 alloy increased from 88.09 MPa to 105 MPa when increasing the welding factors from three to five using central composite rotatable design (CCRD) RSM. The optimum values achieved when the factors increased from three factors (123 mm/min traverse speed, 667 rpm rotational speed, and 4.61 kN axial force) to five factors (traverse speed of 100 mm/min, rotational speed of 893 rpm, axial load of 6.5 kN, 14.8 mm and 4.9 mm for shoulder and pin diameter respectively, and 45.4 HRc hardness of the spindle tool. The analysis of variance (ANOVA) had been given 95% confidence level. In these studies, the UTS of the base metal was 110 MPa [19–21]. More developments focused on above model for AA1100 alloy indicated that the tool rotational speed susceptible than anyone else welding parameters when the spindle rotational speed range increased (622–1037) rpm using central composite design (CCD) six factor five level RSM. An UTS of 105 MPa had been shown by the FSW joints fabricated at 993 rpm rotational speed, 7.84 kN axial load, 72.25 mm/min traverse speed, 40 HRc tool hardness, and shoulder and pin diameters of 14.55 mm and 5.12 mm respectively [22]. In AA1100 alloys studies, beside to the central composite design RSM, a genetic algorithm added for optimizing process parameter [23]. Spindle speed, traverse speed and diameters of pin and shoulder had used as independent variables. The optimum tensile strength achieved of the weldments was 73 MPa as shown in Table 1. As a result, in all studies on Al100, the temper of the alloys did not indicate, and the optimum tensile strength did not access base metal tensile strength.

3.2. Aluminium 2xxx series

Copper is the main alloying part of the 2xxx aluminium alloys. This series is widely used in airplanes industry where their yield strength value above 455 MPa [18]. AA 2014 is valid in two tempers T4 and T6. It is available as heat-treatable alloys and Alclad as corrosion-resistant aluminium alloys. This alloy is having wide range of applications including machines frames and parts especially in pistons and cylinders beside to its main application in

Table 1
Ultimate tensile strength and optimum conditions of 1xxx alloys.

Ref.	Material	Factors	UTS (MPa)		Optimum Parameters		
			Base Metal	Predict	N(rpm)	S(mm/min)	F(kN)
[19]	AA1100	3	110	88	667	123	4.16
[20–21]	AA1100	5	110	105	893	100	6.5
[22]	AA1100	5	110	105	993	72	7.84
[23]	AA1100	5	110	73	1001	62	3.0

aircraft structures. Using Box-Behnken RSM with ANOVA and Genetic algorithm lead to predict an empirical equation for the UTS of AA2014-T4 aluminium alloy under immersed FSW process. The experimental results showed that the obtained tensile strength of 307 MPa less than 25% base metal strength [24]. When the genetic algorithm added, the maximum tensile strength increased to 318 MPa (about 78% of the base alloy strength) when the process parameters were rotational speed of 1077 rpm, traverse speed of 100 mm/min and 18 mm diameter of shoulder while the axial load value did not indicate in this study.

The AA 2219 alloy has good weldability and crack resistance with high strength. It can be found in several tempers T3, T4, T5, T6, T7 and T8. It is can be used in the application of high temperature up to 315 °C [18]. There several studies try to estimate the tensile strength on AA2219-T87 aluminum alloy. A first study selected three-factor, five level CCRD. In this study the predicted tensile strength reached to 285 MPa which is about 61% from the base metal UTS. The predicted UTS achieved at 1639 rpm spindle rotational speed, 90 mm/min traverse speed and axial force of 11.2kN [19]. In the second study, four factor, five level CCD RSM had been used to reduce the experimental conditions. ANOVA used to obtain 95% tensile strength prediction confidence from process parameters which including spindle rotational speed, traverse speed, axial force, and pin geometry. The superior predicted joint strength 220 MPa (55% of base metal ultimate tensile strength) achieved at 1600 rpm spindle rotational speed, traverse speed of 45 mm/min, and axial force of 12kN by using square pin geometry [25] and later, Hooke and Jeeves algorithm had been used to optimize the previous results [26]. It found the ultimate tensile strength improved by 11% to reach to of 244 MPa by using a spindle speed of 1200 rpm, axial load of 12.5 kN and a traverse speed of 51 mm/s with a square pin geometry.

The best results of AA2219-T87 aluminum alloy achieved in the third study where the UTS in friction stir welding reached to 340 MPa (76% UTS of the base metal). The researchers have developed an approach to study the key factors for the optimization of FSW response of AA2219-T87 butt welds using a full-factorial RSM with ANOVA depending upon three parameters with three levels. The parameters of the model were regarded the welding speed, axial force, and spindle rotational speed. The optimized target values of 340 MPa tensile strength were discovered to be with traverse speed of 256 mm/min, axial load of 29.61 kN and rotational speed of 493 rpm [27].

On the other hand, only one attempt used RSM to predict the weldment strength of 2219-T6 alloy. In this article, the researchers developed a mathematical model to get the best welding conditions of a heat-treatable 2219-T6 alloy for underwater FSW. A Box– Behnken experimental design with three levels was selected to predict the relation of joint strength (response) and the welding parameters (variables). The depth of shoulder plunge, traverse speed and tool rotational speed were deemed as welding parameters [28]. The results indicated that the ultimate tensile strength reached to 360 MPa (83% of the base metal UTS) and it was achieved at 600 rpm, 0.3 mm, 200 mm/min as the rotational speed, depth of shoulder plunge and traverse speed respectively, while the study did not indicate the effect of the axial force.

AA 2024 alloy is very good machinability in the T3, T4, T5, T6, T7 and T8 tempers. Despite its fair corrosion resistance, Alclad 2024 is good corrosion resistance. Structural of aircraft and automotive parts consider the main applications of this alloy [18]. Three studies tried to predict the behaviour of the tensile strength of AA 2024 alloy using RSM. One of the studies did not indicate the temper of the aluminium alloy [29], in this study, a rolled sheet welded by FSW using CNC machine. The RSM matrix consisted of 3 factor 5 levels where tensile strength represents the response and the traverse speed, rotational speed and shoulder diameter represent the process variables. The 295 MPa optimum tensile strength achieved at 62 mm/min (traverse feed), 1436 rpm (rotational speed), and 15.48 mm tool shoulder diameter. The achieved UTS was about 60% from the base metal UTS. The second study, CCRD three-factor, five level response surface methodology was used for FSW of AA 2024-T3 alloy. The results indicated that the optimum tensile strength was 288 MPa (63% of base metal) at 1463 rpm, 67 mm/min and axial force of 7.7 kN [19]. In the third study, a newly designed hexagonal cross-section pinned tool with three different diameters used for joining AA2024-T6 aluminium alloy on FSW. RSM was employed to develop the regression model using four factors, three levels Box-Behnken experimental design [30]. UTS increased gradually to a superior value of 310 MPa when rotational speed increased up to 900 rpm and then declined with additional growth in tool rotational speed. The corresponding values for maximum tensile strength achieved at hexagonal cross-section pin diameter of 5 mm, welding traverse speed of 50 mm/min and axial load of 24.5 kN. All results of Al 2xxx series indicated in Table 2.

3.3. Aluminum 5xxx series

Magnesium is the main element in both 5xxx Wrought Alloys and 5xx.x Casting Alloys. These alloys are extremely resistant to corrosion and are well weldable. This is partly why 5xxx Aluminum Series alloys have been used in a broad spectrum of chemical processing, food handling equipment, construction products and applications containing seawater exposure [18]. In this section, two sets of these alloys had been discussed: AA5059 and AA5083.

AA5059 is a newly advanced protection grade aluminum alloy, its cannot be heat treated but it can be easily welded. Applying the FSW on AA5059 alloy indicated that the predicted UTS was 294 MPa (77% of base metal) which was achieved under conditions of 25 mm/s welding speed, 950 rpm tool rotational speed and an axial load of 3.4 kN by using central composite design RSM with ANOVA [31].

In extreme settings, aluminum AA5083 is renowned for outstanding performance. It has the maximum UTS of the non-heat treatable alloys with a value of more than 300 MPa. In this review, both AA5083H111 and 5083-H321 aluminum alloys had been discussed. For AA5083H111 aluminum alloy, it found that when a straight square pin profile FSW was executed and using five-level three-factor CCRD Response surface methodology with analysis of variance (ANOVA), the highest UTS value attainable was 260 MPa at 1000 rpm tool rotational speed, 69 mm/min traverse speed and axial force as function of time of 1.33 t [32]. On the other hand, there was an attempt to maximize the tensile properties of

Table 2
Ultimate tensile strength and optimum conditions of 2xxx alloys.

Ref.	Material	Factors	UTS (MPa)		Optimum Parameters		
			Base Metal	Predict	N (rpm)	S (mm/min)	F (kN)
[19]	AA2219-T87	3	470	285	1639	90	11.2
[19]	AA2024-T3	3	460	288	1463	67	7.7
[24]	AA2014-T4	3	410	318	1077	100	–
[25]	AA2219-T87	4	402	220	1600	45	12
[26]	AA2219-T87	4	402	244	1200	51	12.5
[27]	AA2219-T87	3	450	340	493	256	29.6
[28]	AA2219-T6	3	432	360	600	200	–
[29]	AA2024	3	452	295	1436	62	–
[30]	AA2024-T6	4	410	310	900	50	24.5

FSW in 5083-H321 aluminum Alloy joint using real time user interface (GUI) to get force footprint diagram [33]. During this study, temperature, torque, and multiple force responses were recorded to predict a weld tensile strength using RSM. The authors studied the effect of combination of rotation angle and bending force together with applied torque, temperature, and vertical load in case of taking tool rotational speed and welding speed as constant at 600 rpm and 150 mm/min receptivity. The optimum tensile strength was produced when the values vertical force 9.3 kN, rotational angle 34.6°, temperature 558. °C and torque of 58.3 Nm. All results of Al 5xxx indicated in Table 3.

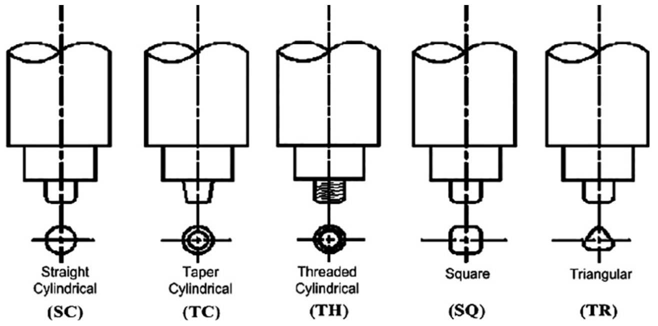

Fig. 3. Pin geometry types [29].

3.4. Aluminum 6xxx series

The high strength and very excellent corrosion resistance of the heat treatable of the 6xxx series wrought alloys make them as highly appropriate for multiple applications of structure, construction, marine and process equipment. AA6061 alloy is considered the most widely used from 6xxx series. Besides to its good corrosion resistance, it is having a good ability to weld and good formability. Depending on their tempers, the tensile strength of these alloys ranges is 124–310 MPa [18]. There are more than 10 studies tried to determine the optimum tensile strength of AA6061 aluminium alloy in both similar and dissimilar alloys.

As well as the familiar welding parameters (spindle rotational speed, axial force, and traverse speed), the influence of pin geometry on the joint strength had been studied [34–35]. Four factors and five levels CCD had been applied. In the first study, a prediction model to superior tensile strength used the Hooke and Jeeves algorithm. The optimized and experimental values were closely agreement. The max predicted tensile strength was 200 MPa at rotational speed of 1250 rpm, axial load of 7.25kN, traverse speed of 90 mm/min by using a pin of square profiled while in the second study, the predicted model had been achieved 95% confidence by using ANOVA. The max predicted tensile strength was 177 MPa at rotational speed of 1200 rpm, axial load of 7kN, traverse speed of 75 mm/min by using square pin profiled tool (Fig. 3).

A three factor five level CCRD RSM applied on experimental results of AA6061-T4 aluminum alloy joining by FSW for predicting the tensile properties [36]. The study indicated that, with an increasing of traverse speed and rotational speed, the UTS of AA 6061-T4 joints increased. The optimal parameters to achieve maximum joint strength were traverse speed of 78 mm/min, spindle rotational speed of 920 rpm and 7.2kN axial load. This study indicated that the value of predicted UTS was 160 MPa which it was about 79% of the base metal strength.

There are several trials on the aluminum alloy AA6061-T6, the influence of the familiar FSW parameters had been studied in [19]. In this study, a central composite design matrix RSM used to investigate an empirical relationship of different aluminium alloy joints, the achieved result of the UTS was 183 MPa at 1178 rpm spindle rotational speed, 115 mm/min traverse speed, and axial force of 8.2 kN.

Furthermore, the effects of tool hardness and pin and shoulder diameters besides to the influence of familiar welding process parameters are studied [37] and with the effect of corrosion rate [38]. In both studies, six factors, five level CCD matrix used while the ANOVA technique was used to optimize the developing empirical relationship. The highest value of tensile strength was 222 MPa where it achieved at 1400 MPa, 60 mm/min and 8kN as values of spindle rotational speed, traverse speed and axial load, respectively. In the second study, the effects of corrosion rate added, the superior value of tensile strength slightly increased by 1.3% to 225 MPa where it was recorded at 1150 rpm tool rotational speed, traverse speed of 84 mm/min, axial load of 7.16 kN, tool hardness of 45HRc with diameters of shoulder and pin of 15 mm and 5 mm, respectively.

Another attempt on AA 6061-T6 aluminum alloy done by using three parameters, three levels CCD matrix RSM to predict the yield strength and UTS of thickness rolled plates that joining by FSW

Table 3
Ultimate tensile strength and optimum conditions of 5xxx alloys.

Ref.	Material	Factors	UTS (MPa)		Optimum Parameters		
			Base Metal	Predict	N (rpm)	S (mm/min)	F (kN)
[31]	AA5059	3	485	294	950	25	3.4
[32]	AA5083H11	3	308	260	1000	69	1.33 t
[33]	AA5083H321	3	350	344	600	150	9.3

[39]. This study indicated that a low welding speed of 30 mm/s with increased axial force to 9kN and 1199 rpm rotational speed was quite enough to increase the UTS to 198 MPa which was considered as good value for AA 6061-T6 alloys.

A tilt angle influence on UTS value of AA6061-T6 joint during FSW was studied using four parameters and five levels CCD [40]. In this study, the input variables which was used to optimize the tensile strength are rotational speed, traverse speed, pin profile beside to the tilt angle. Results indicated that the UTS of 288 MPa had been achieved by using simple cylindrical tool at 1150 rpm rotational speed, 70 mm/min traverse speed, tilt angle of 3°. The achieved UTS was about 92% of the base metal value. This study did not indicate the effect of the axial load.

AA 6082 alloy is most frequently used for machining because of the high strength and outstanding corrosion resistance properties. limited studies were dealing with prediction of tensile strength of this alloy using RSM. A five-factor, five-level CCD RSM applied at 95% ANOVA confidence level to expect yield strength of double side FSW 6082-T6 alloy. Beside to the familiar FSW parameters (rotational speed and traverse speed and tool geometry), the effect of shoulder penetration was studied [41]. In this article, a square pin profile, 5° shoulder profile, tool rotational speed of 1300 rpm, traverse speed of 192 mm/min and shoulder penetration of 0.04 mm had been exhibited. A superior tensile strength of 105 MPa and joint efficiency of 96.6% had been achieved (Table 4)

3.5. Aluminum 7xxx series

The 7xxx series are the most powerful aluminum alloys possible with yield strengths more than 500 MPa. AA 7075 alloy is the most widely used alloy in the 7xxx series. Several studies were applying RSM on the AA7075–T6 alloys for developing a mathematical model and predicting the tensile strength.

In In the first study, six factors (spindle rotational speed, traverse speed, axial load, tool hardness and diameters of pin and shoulder), five level central composite designs had been used. ANOVA, regression analysis and design of experiments were used to develop the mathematical relationships. A superior tensile strength of 375 MPa was observed by the FSW joints fitted with the optimized parameters of 8.29 kN axial load, spindle rotational speed of 1438 rpm, 67 mm/min welding speed, shoulder diameter and pin diameter of 15.54 mm and 5.13 mm respectively, and 600 HV tool hardness [42]. In the second study, three factors only of the same material (rotational speed, traverse speed and axial load) had been studied, the result of weldment strength was very closed to the prevoius study despite of changing the axial load and rotational speed; it was 378 MPa at 1799 rpm, 70 mm/mim, 14.4 kN [19].

The third study proposed empirical equations to predict joint strength and grain size of rolled plates of AA7075-T6 after friction stir welding process using RSM. Five-level six-factor CCRD matrix applied to optimize rotational speed, axial load, and traverse speed beside to pin and shoulder diameters and tool hardness [43]. According to the study results, the UTS reached to 365 MPa which means about 75% of the base metal, this value achieved at 1400 rpm, 60 mm/min and 9 kN as values of rotational speed, traverse speed and axial load, respectively.

For AA7039 aluminum alloy, there was an attempt to compare the Artificial neural network (ANN) with a traditional RSM technique to predict the tensile strength of AA7039 aluminium alloy after friction stir welding process. In RSM, three factors with three-level and CCD had been used where the welding parameters were welding speed, rotational speed, and axial load. Regarding to the RSM, an UTS of 319 MPa was achieved for the process parameters of 1460 rpm rotational speed, 40 mm/min traverse speed and axial load of 6.5 KN [44]. The results shown that ANN can model the FSW process more accurately than response surface mythology (Table 5).

3.6. Dissimilar aluminum series

One of the main advantages of friction stir welding process, it was succussed to welding the dissimilar alloys which cannot be welding in fusion welding processes. The AA6061 aluminum alloy is the main alloy in major dissimilar aluminum series. Al-TiCp fusion welding is hard and has been a continuous challenge for manufacturers so far. A good weldment of Al-TiCp achieved by FSW where AA6061 aluminum alloy is used [45]. In this study, RSM used with regression equation to predict UTS. Design matrix of five factor five level ½ factorial design uses for developing the mathematical model. The pin geometry had a superior influence on tensile strength of FSW joints followed with the traverse speed while the effect of rotational speed was limited on the tensile

Table 4
Ultimate tensile strength and optimum conditions of 6xxx alloys.

Ref.	Material	Factors	UTS (MPa)		Optimum Parameters		
			Base Metal	Predict	N (rpm)	S (mm/min)	F (kN)
[34]	AA6061	4	344	200	1250	90	7.25
[35]	AA6061	4	344	177	1200	75	7
[36]	AA6061-T4	3	205	161	920	78	7.2
[19]	AA6061-T6	3	283	183	1178	115	8.2
[37]	AA6061-T6	6	283	220	1400	60	8
[38]	AA6061-T6	6	283	225	1150	84	7.16
[39]	AA6061-T6	3	283	198	1199	30	9
[40]	AA6061-T6	4	312	288	1150	70	–
[41]	AA6082-T6	4	271	105	1300	192	–

Table 5
Ultimate tensile strength and optimum conditions of 7xxx alloys.

Ref.	Material	Factors	UTS (MPa)		Optimum Parameters		
			Base Metal	Predict	N (rpm)	S (mm/min)	F (kN)
[42]	AA7075–T6	6	485	375	1433	67	8.29
[19]	AA7075–T6	3	410	378	1799	70	14.4
[43]	AA7075–T6	6	485	365	1400	60	9
[44]	AA7039	3	383	319	1460	40	6.5

strength. The study found that the tensile strength value reduced by 3% when it compared with cast aluminum strength.

FSW was effective in bonding AA7075 and AA6061 alloys. Three factors, three levels CCD matrix with the ANOVA analysis had been used in RSM prediction studies. The first study found that UTS of the FSW joints improves with rotational and traverse speeds increasing up to a maximum value, and then reducing. The optimum UTS was of 198 MPa when applying an axial load of 6 kN, rotational speed of 1200 rpm and traverse speed of 30 mm/min [46]. Another study successed in increasing the ultimate tensile strength 18% to be reached to 233 MPa during FSW, this value was achieved at a rotational speed of 1100 rpm, axial load 8KN using cylindrical tool [47]. Friction stir welding also successed to join AA6061 and ZrB2, in this work, an aluminum matrix composites (AMCs) produced by adding a quantity particle of ceramic to aluminum alloys had been used. A CCRD of four factors, five levels have been applied in RSM analyses. The optimized process parameters were 1155 rpm rotational speed, traverse speed of 48.8 mm/min, axial load of 5.9 kN, and 10 wt% of Zirconium Boride while the predicted UTS is 229 MPa [48].

The series 6xxx and 2xxx also had been succeed in welding through friction stir. In this field, AA6061 and AA2024 alloys studied by using RSM based on Grey Relational Analysis approach together with Principal Component Analysis to optimize process parameters. Spindle rotational speed, traverse speed, axial force, and geometry of pin were listed as welding parameters. The optimum UTS of 141 MPa was achieved using squared pin and 1700 rpm tool rotational speed, 60 mm/min traverse speed and axial load of 6 kN [49]. Furthermore, the AA2024 can be joined with AA7075 alloy. Three levels CCD RSM applied to predict the influence of welding parameters on the AA7075-T6/AA2024-T3 weldment strength. This study shown that the tensile strength of the weldment proportional with the rotational speed up to 1050 rpm and traverse speed up to 15 mm/min and then UTS decreased. The UTS of 269 MPa is obtained at a rotational speed of 1050 rpm and traverse speed of 15 mm/min [50].

Also, a study predicted a model for UTS and nugget hardness depending on rotational speed, welding speed and stirrer shape of friction stir welded AA5083/AA1050 alloys. In this study, ANOVA used with main influence plots to set the optimum level for every parameter. The predicted and experimental values were agreed with a R2 of 0.93 and 0.82 for nugget hardness and UTS, respectively. The traverse speed of 71.62% was found as the most important factor on the UTS while tool rotational speed and stirrer geometry each of them did not access than 10% of the total effect [51]. The optimal UTS of 95.89 MPa was obtained using triangular profile geometry with 900 rpm and 250 mm/min as conditions of rotational and traverse speeds, respectively.

3.7. Pin profile effects

Most FSW studies are used square pin profile because of its better stirring ability and higher frictional heating which lead to forming a homogeneous visco-plastic material and preventing grooves and cracks defects [52]. In this manuscript, the reviewed studies are varying according to use of pin geometries such as squared pin [25,26,32,34,35,41], cylindrical [40,48], hexagonal cross-section [30] and triangular [51]. Despite of this variation of pin geometry, their effects on the resulted tensile strength can be negligible as compared with tool rotational speed and welding speed. The high plastic deformation of aluminum alloys at high rotational speed is leading to form a layer around all types pins profiles and making all of them as like the straight profile, this layer reducing the effect of pin profile changing on tensile strength as compared with rotational speed.

4. Conclusions

The Response Surface Methodology is an active technique to predicate the behaviour of the tensile strength and given a statistical equation for friction stir welding process. Furthermore, it is also creative method to find the optimum welding parameters to stratify the ultimate tensile strength. several concluding points from this review are given below.

1. Most studies on optimizing welding process parameters and predicting tensile strength of FSW joints were focused on alloys 1xxx, 6xxx and 2xxx with few studies on 5xxx and 7xxx while there are very limited studies on 3xxx, 4xxx.
2. The main FSW parameters were tool rotational speed, traverse speed, and axial load. Sometimes the reviewed studies were expanding to include the effect of dwell time and geometry of the tool.
3. The values of optimum tensile strength had been ranged from 73 MPa −105 MPa for AA1100 alloys, 219 MPa-360 MPa for 2xxx series, 255 MPa-294 MPa for 5xxx series, 104 MPa-288 MPa for 6xxx series. 319 MPa-377 MPa for 7xxx series.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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