Identification of Process Parameters and Optimization Techniques for AA 6061 in FSW: State-of-the-art

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Abstract. Friction Stir Welding (FSW) is a new method of solid state joining of metals and nonmetals as a substitute technology applied in high strength alloys that are challenging in joining processes in traditional ways. At this contemporary epoch, many transportation industries utilize friction stir welding by its light weight higher strength weld properties. However, many problems are associated and diminution on the weld quality by a shortage of skills. One of the key challenges is selecting an appropriate optimization techniques and process parameters for single and multiple response studies. The current scenario, focused on the determination and identification of appropriate process parameters and optimization techniques for welding of AA6061 material using friction stir welding. All process parameters and optimization methods are intensively studied from the previous kinds of literature and identified appropriate process parameters for AA6061 materials. Based on the results, process parameters namely rotational speed at 43.7%, traverse speed at 17.29%, tool tilt angle 7.46%, axial force of 7.09%, ratio of tool shoulder-to-pin size 3.69%, other parameters are 1.73% contributions for achieving higher mechanical properties (tensile and hardness) of AA6061.

Keywords: Process parameters · ANN · GA · GRA · RSM · Taguchi

1 Introduction

One of the methods of joining methods at solid state is friction stir welding. This technique termed as 'ecological sound' method because of energy effectiveness and environmentally friendly. Friction stir welding invented in Cambridge, UK by Wayne Thomas and his coworker in 1991 [1, 2]. This joining process is applied widely for similar and non-similar metallic and non-metallic materials in manufacturing sectors especially in transportation industries such as aerospace, rail ways, defense, wagons and other micro-electronics due to for many mechanical property advantages [3–9]. It provides numerous advantages over conventional welding such as a higher weld bead strength than weight ratio, it does not utilize consumable electrode and filler materials, less power consumption, significantly low HAZ, and there is no smoking during joining process [10–12]. At this contemporary epoch, the usage of magnesium alloy is exponentially increased due

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to higher strength-to-weight ratio. Magnesium is about 30% lighter than aluminum and four times lighter than steel with density of 1.8 g/cm^3 [12]. AA6061 is categorized under 6xxx series of aluminium alloy and the major constitutes element are magnesium and silicon, respectively. It has a good mechanical property, easily weldable, considered as a common alloy for general uses and in aerospace applications; it is used to construct wing and fuel silage parts [13–15]. The main aim of this study is to determine and identify appropriate process parameters and optimization techniques for the quality criteria on tensile and hardness strengths of AA 6061material by friction stir welding method.

2 Process Parameters of FSW

In design of experiments while optimization is going to be carried out, there are at least two main process parameters; controllable and fixed ones. Controllable parameters are those parameters where one can control based on the specified levels during execution of experiment. While, fixed parameters are parameters which will not altered throughout the experiments [16]. FSW process parameters namely controllable and fixed are summarized and shown in Fig. 1.

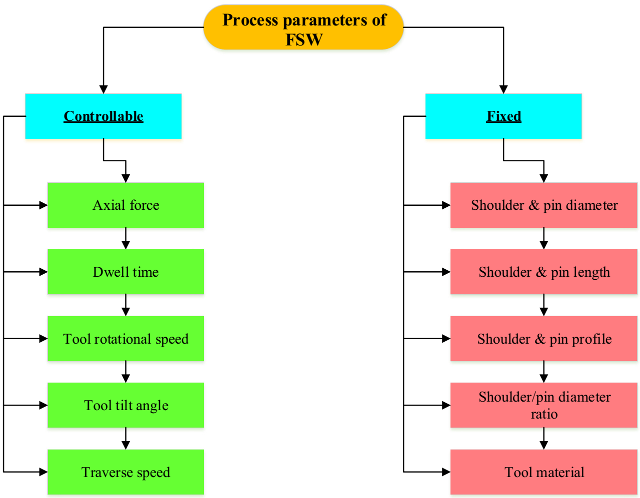

Fig. 1. Process parameters of FSW [17]

The above shown process parameters plays a dynamic role in affecting the quality criteria of point of interest plus the metallurgical properties of the weldment [17–20]. Therefore, to get admirable welding quality, optimization of the process parameters is the best alternative.

2.1 Control Process Parameters

Axial Force: Axial force which tends to hold pressurizing the weldment has a significant role in a proper mixing of heated materials. This force will impede formation of cavities in the retarding side of the weldment [21]. Higher axial force induces higher generation of heat in the base metals. Owing to the higher heat input, metal gets softened and extruded as flash, resulting tunnel defect in the middle of base metals. This force has no major alteration on microhardness at the nugget region. However, tensile strength corresponding to the axial force of the tool [22, 23].

Dwell Time: The duration of tool that plunged into the weld material at desired depth and a given rotational speed without translational motion is referred to this time. It is the most foremost joining process parameter for weldment strength next to rotational speed and welding speed or traverse speed [24].

Tool Rotational Speed: Prime motion imparted to the tool is one of the most dominant process parameters. This dominant process parameter is rotational speed of a tool. This rotational speed produces a substantial heat and string effect which will help to mix material flows. With the traverse movement of this tool with rotating at a certain number it moves the soften material from front to back and completing the weldment. It is the highest and most influential parameter [25, 26]. A higher rotational speed produces higher temperature and abandoned wider heat-affected zone on the base metals [27].

Tool Tilt Angle: The angle between the tool axis and the nominal axis of base metal referred as tilt angle. Tool tilt has a significant effect on generation of heat, metal follow movement, and consolidation. Tool tilt angle helps in impeding of flowing materials from being ejected [28]. The higher tool tilt angle may increase the wear rate of a tool and even further failure [29].

Traverse Speed: In some other words-welding speed. This parameter is one of the influential process parameters. On selecting of levels on influential process parameters, care shall be taken. The lower welding speed produces fine grain structure and exhibits with the best corrosion resistant [30] and also, the peak temperature and heat input of the joint increases during the process. On the other hand, higher welding speed will yield in higher mechanical properties of (hardness and tensile), but lower elongation of joint [31].

2.2 Fixed Process Parameters

Fixed process parameters are those of process parameters where no alteration is carried out throughout the experimental execution.

Tool Profile (Pin): The movement of heated and sot material will be governed by the shape and geometrical shape of the pin. This movement will significantly influence the plasticizing of material [32, 33].

Tool Design

- Geometric configuration shall be uncomplicated as to minimize the cost of a tool.

- It shall be able to move and stir substantial amount of material.

Tool design is a curial part of the design in this kind of joining process. Heat generation is dependent on a kind and type of tool configuration. This design section includes two main parts; shoulder and pin [34].

Tool Geometry-Shoulder (D): In solid state (friction stir) joining method, heat is generated through rotational speed with the help of tool shoulder geometry. The friction of sticking and sliding is depending on the tool shoulder geometry [35].

Tool geometry-pin length: one of the prime factors in friction stir joining method tool design is the design and choice of the pin length. For one sided friction welding process, the pin length and the thickness of base metal shall not be equal. If the length of the tool pin and the base metal is equal the weldment will not be effective. According to the study, the pin length must be at least less than 0.3 mm than the base metal. With this size of the pin, the shoulder should touch the base metal surface and root will be good [35].

Tool Geometry-Pin Size (d): One of the most notable process parameters is the pin size (diameter). This geometry will affect the weldment mechanical property and the weld cross sectional area. This is because the stirring in the weld is mainly caused by the pin dynamic motion [36]. It greatly affects the size of the weld region [37].

Tool geometry-D/d ratio: the ratio of the tool geometry shoulder diameter to pin diameter is one of the most essential process parameters in friction stir welding process [38].

Tool Material: In all the tool geometry, selection of tool material is very important. Since, friction stir welding is a process of joining by making use of heat generated in the tool and the base metal, selection of tool material is undoubtably very vital. A noble tool material shall have the following features:

- good strength and wear resistance
- good dimensional consistency
- good coefficient of friction between the base metal
- nonreactive with the base metal
- good machinability for ease of shaping
- good hot hardness
- affordable cost [35, 39].

3 Design of Experiment

Design of experiment (DOE) is an efficient way of executing experiment. In addition to this, this can help to analyzing and interoperating results [40, 41]. The method defines and examining all the possible combinations and situations in conducting experiments. Design of experiment commonly used for comparison, variable screening, transfer function identification, system optimization and robust design [40, 42].

3.1 Selection of Orthogonal Array

In the process of determination, the optimal process parameters, the combination of possible number of trials and parameter settings are arranged in systematic way to cut out the volume of experimental executions [43]. This orthogonal array is developed from Latin square. Before considering the type of orthogonal array there must be considering two points:

- number of controllable process parameters
- number of levels within the construable process parameters.

In addition to this, to choose sustainable OA, total degrees of freedom (DOF) are calculated. The DOF are the number of contrasts to make between design parameters. For example, a three-level design parameter counts for two degrees of freedom [45].

3.2 Optimization Methods of FSW for AA 6061

There are different and numerous kinds of optimization techniques employed in process parameters optimization of AA 6061 material. Some of them are discussed below.

Artificial Neural Network (ANN): ANN is biological inspired computational approach optimization technique. ANN is like human neural configuration which can learn from the past memory and envisaging to the future [46, 47]. This kind of optimization method is capable of solving un-anticipated dynamic problem. The performance of ANN is measured by the error between the outcome, training time, the complexity of the system [48]. ANN is widely used for medicine, finance, engineering, geology, physics and optimization process. The process is widely used in mono and multi-responses optimization processes. The basic steps involved in ANN are shown in Fig. 2.

Genetic Algorism (GA): GA is a search, computational and optimization algorithm inspired by natural evolution. This method was introduced by Jhon Holand in 1970 [51–54]. This algorithm employs Darwin theory of evolution and used layered coding to show the slicing process [55, 56]. GA espouses the productive strategy, which is based on the proper amount, to calculate the relative adaptive value of the individual and decide how much the probability is to put in to a mating pool and make the next round of optimization [57]. This optimization process used to analyze single and multiple responses optimization processes. The application areas of the GA are the parametric design of aircraft, robotic trajectory generation, strategy acquisition for simulated airplanes, scheduling medical diagnostics, identifying criminal suspects, data science and may more [58, 59].

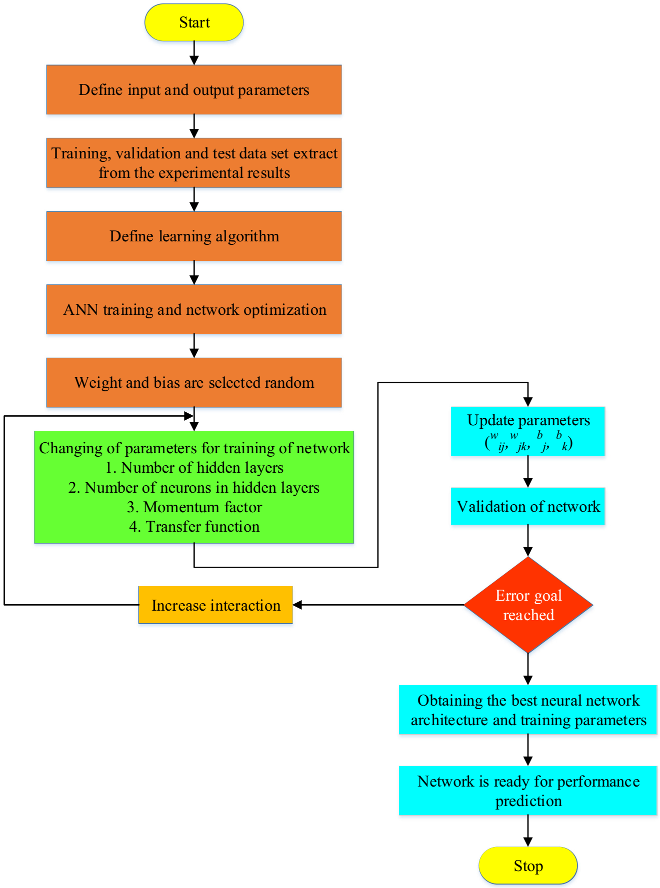

Fig. 2. Flowchart of artificial neural network [49, 50]

The flow step of genetic algorithm is shown in Fig. 3 below.

Grey Relational Analysis (GRA): GRA is a method for making decision based on Grey method. This method is developed by Deng Julong in 1989. This method utilized in advanced way of Taguchi optimization method. One of the drawbacks of Taguchi method is it considers only single response. However, GRA is useful in making of multiple response optimization [60–63]. Generally, this method converts multi response quality criteria in to single one. However, the drawback of this method is it is not suitable for mono response [64]. The procedures for establishment of this method is shown in Fig. 4.

Response Surface Method (RSM): RMS is a group of mathematical and statistical method designed by Box and Wilson in 1951. This technique utilized for the design of experiments describes the relationship between process variables and product quality characteristics [70–72]. This method can check the interaction between factors under

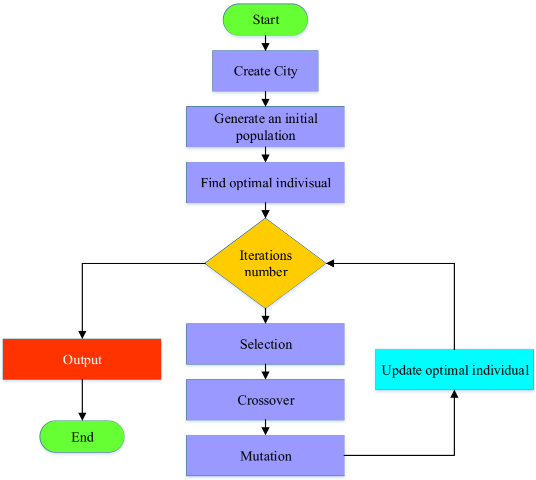

Fig. 3. Flowchart of Genetic Algorithm [51, 59]

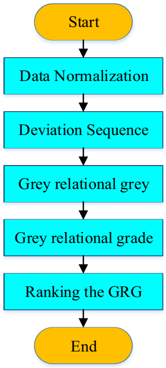

Fig. 4. Flowcharts of grey relational analysis method [65–69]

different conditions [73, 74]. In addition to this, it is suitable for single and multiple response optimization method [75]. The key pro of RMS is a reduced number of experimental trails required to assess multiple parameters and their interactions [76]. This method can be further applicable in many optimization fields [70, 71, 77] (Fig. 5).

Taguchi Method: This method is developed by the late Dr. Genechi Taguchi in 1940 [78, 79]. This method is for universal field of specialization [79, 80]. This method is applicable making use of orthogonal array scheme [79, 81]. Moreover, the method data interpretation is carried out by utilizing signal-to-noise ratio analysis. Signal-to-noise ratio is a measure of robustness of the system [82, 83]. Generally, the process is suitable for optimizing the mono response quality criterion. The flow step of this method is shown in Fig. 6 below.

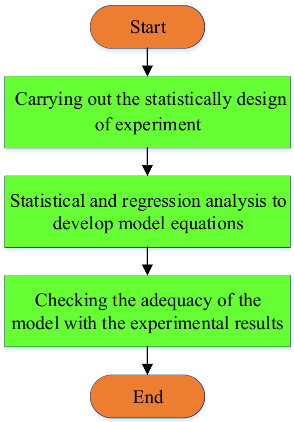

Fig. 5. Chronological steps of RSM [72, 74]

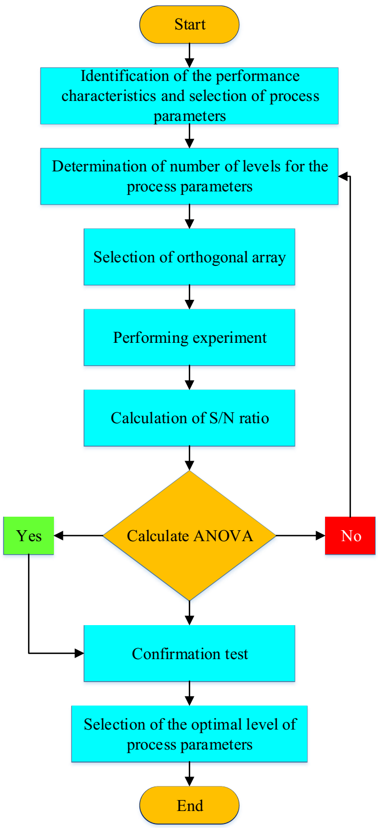

Fig. 6. Chronological flowcharts of Taguchi method [84–87]

4 Results and Discussions

4.1 Determination of Parameters

With all the possible combinations of all control process parameters filtered out by different mechanism; like fish bone diagram or cause and effect, experimental trails executed and results recorded. With making use of suitable optimization method, the possible combination of optimum parameters will be determined. Statistically determination of the analysis of variance will then conducted to find out the significance of control process parameters. Different scholars using ANOVA to identify parameters of how much percent contributing to the response of the study. Therefore, in the present study, reviewed and

Table 1. Determination of process parameters

Parameters with % contribution												
No	A.F	T.S	R.S	T.A	T.P.P	D/d	DT	DTP	PD	N^{o}P	Error	Reference
1	38	11	51								0	[18]
2	21.8	26.1	49.7								2.4	[88]
3		9.32	70.44			19.10					1.14	[89]
4			32.08	48.17		17.53					2.19	[90]
5	6.9	18.43	74.67									[91]
6		50.63	19.17	8.20			21.98					[92]
7	28.3	28.3	67								3.3	[93]
8		20.6	12.30	26.3							40.67	[94]
9		33	62							5		[95]
10	21.5	22.4	24.68		26.23						5.11	[96]
11		34.8	47.30	8.79							9.04	[97]
12	21	33	41								5	[98]
13		6.14	53.0	36.9								[99]
14		38.0	24.4	33.8							3.8	[100]
15		2.60	15.2		74.49						7.65	[101]
16	0.29	11.0	59.2								29.39	[102]
17		13.5	67.2	15							4.3	[103]
18	17.6	35.3	46.2								0.64	[44]
19		15.45	80.45						3.92		0.17	[104]
20	15	35	19		23						8	[105]
21		23.8	65.2	6.3							4.7	[106]
22		8.25	58.05					33.1			0.6	[107]
23		0.03			38.12	58.6					3.23	[108]
24			96.24	0.06	0.41						3.29	[109]

Where:**A.F:** Axial force,**T.S:** Traverse speed, **R.S:** Rotational speed, **T.A:** Tilt angle, **T.P.P:** Tool pin profile, **D/d:** Shoulder diameter/tool diameter ratio, **DT:** Dwell time, **DTP:** Diameter of tool pin, **PD:** Plunge depth, **N^{o}P**: N^{O} of pass.

determined the most significant process parameters that strongly improved the hardness and tensile strength of AA 6061 are study. Parameters collected from previous similar studies by looking at its percent of contributions on the above responses and make it an average to identify appropriate parameters for AA 6061 materials (Table 1 and Fig. 7).

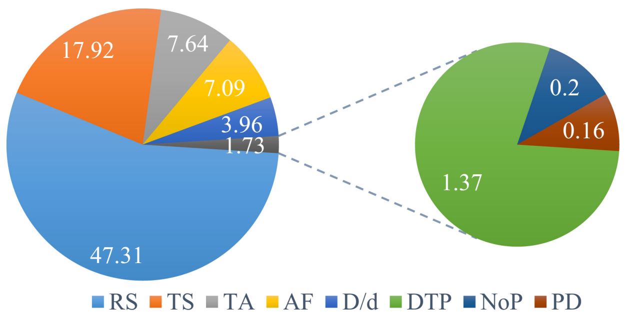

Fig. 7. Determination of process parameters for FSW

Grounded to the above table and figure, rotational speed of 47.31%, traverses speed of 17.92%, tool tilt angle 7.64%, axial force 7.09% D/d ratio 3.96%, and other parameters are 1.73% contribute for getting a higher hardness and tensile strength of AA6061. The prime mover, rotational speed, welding speed, tool inclination angle, and central force are most critical and capital virtue process parameters for AA 6061 materials as per their weights (Table 2).

4.2 Determination of Optimization Techniques

Table 2. Determination of optimization techniques for 6061 AA materials

No	Parameter	Optimization techniques	Material	Reference
1	R.S, W.S & A.F	ANN	6061AA	[110]
2	R.S, & W.S	ANN	6061AA & 7075AA	[111]
3	R.S, & W.S	ANN & RSM	6061AA	[112]
4	R.S, W.S, & A.F	ANN & Taguchi	6061AA & 2024AA	[44]
5	Sd, Sgd, Pl, P.A, Pd, & P.L	ANN & Taguchi	AA6061-T6	[113]
6	R.S, W.S, A.F, & P.P	GA & RSM	2024AA & 6061AA	[114]
7	R.S, W.S, and A.F	GA & RSM	6061AA & 2014AA	[102]

(*continued*)

Table 2. (*continued*)

No	Parameter	Optimization techniques	Material	Reference
8	R.S, W.S, A.F, and P.P	GRA & RSM	2024AA & 6061AA	[96]
9	R.S, W.S, A.F, Pl, Sd, & Pd	GRA & RSM	6061AA	[115]
10	R.S, A.F, P.P, & Al.M	GRA & RSM	6061AA & 7075AA	[116]
11	R.S, W.S, A.F, & P.P	GRA & RSM	AA6061-T6 & 2024AA	[117]
12	R.S, W.S, Pl, & Od	GRA & Taguchi	AA6061-T6	[118]
13	R.S, W.S, & Td	GRA &Taguchi	5083AA & 6061AA	[104]
14	Ts.P, A.F, R.S, W.S & T.A	GRA & Taguchi	7075AA & 6061AA	[119]
15	R.S, W.S, & Pl	GRA & Taguchi	6061AA	[120]
16	R.S, W.S, & P.P	GRA & Taguchi	AA6061-T6 & AA7075-T6	[121]
17	R.S, W.S, & A.F	GRA & Taguchi	AA6061-T6	[91]
18	R.S, W.S, A.F, & P.P	RSM	6061AA & 7039AA	[122]
19	R.S, W.S, A.F, Pd, Th, & Sd	RSM	6061-T6	[123]
20	R.S, & W.S	RSM	6061AA	[124]
21	R.S, W.S, T.A, Pl, Pd, & Sd	RSM	6061AA	[125]
22	R.S, W.S, T.A, & P.P	RSM	AA6061-T6	[126]
23	R.S, W.S, & A.F	RSM	AA6061-T6	[4]
24	R.S, W.S, Sd, & T.A	RSM	AA5083-H12 & AA6061-T6	[127]
25	R.S, W.S, & A.F	RSM	AA6061-T6 & AA7075-T6	[128]
26	R.S, W.S, & T.A	Taguchi	AA6061-T6 & AA6951-T6	[97]
27	R.S, W.S, & T.A	Taguchi	AA6061-T6 & AA5083-H321	[100]
28	R.S, W.S, & Tsd	Taguchi	6061-T6	[129]

(*continued*)

Table 2. (*continued*)

No	Parameter	Optimization techniques	Material	Reference
29	R.S, W.S, & T.A	Taguchi	6061-T6 & AA5083-H321	[103]
30	R.S, W.S, & N.P	Taguchi	Al6061-Al7075	[95]
31	R.S, W.S, and T.A	Taguchi	6061-T6 and AA5083-H321	[106]
32	R.S, W.S, & T.A	Taguchi	5083AA & 6061AA	[94]
33	R.S, W.S, & A.F	Taguchi	6061AA	[18]
34	R.S, W.S, & P.P	Taguchi	6061AA	[130]
35	R.S, W.S, & T.A	Taguchi	AA6061-T6 & AA2024-T0	[131]
36	R.S, W.S, & A.F	Taguchi	6061AA	[88]
37	R.S, W.S, & T.A	Taguchi	6061AA	[132]
38	R.S, W.S, & T.A	Taguchi	6061AA	[133]
39	R.S, W.S, & A.F	Taguchi	AA6061-T4	[93]

Where:**R.S** = Rotational speed, **W.S** = Welding speed, **A.F** = Axial force, **P.P** = Pin profile, **T.A** = Tilt angle, **N.P** = Number of pass, **Tsd** = Tool shoulder diameter, **Pl** = Pin length, **Pd** = Tool geometry-Pin diameter, **Sd** = tool geometry-Shoulder diameter, **Th** = Tool hardness, **Sgd** = Shoulder groove depth, **P.A** = Pin angle, **P.L** = Pin lead, **Al.M** = Aluminum material, **Td** = Tool depth, **Od** = Offset distance, **Ts.P** = Thickness of plate.

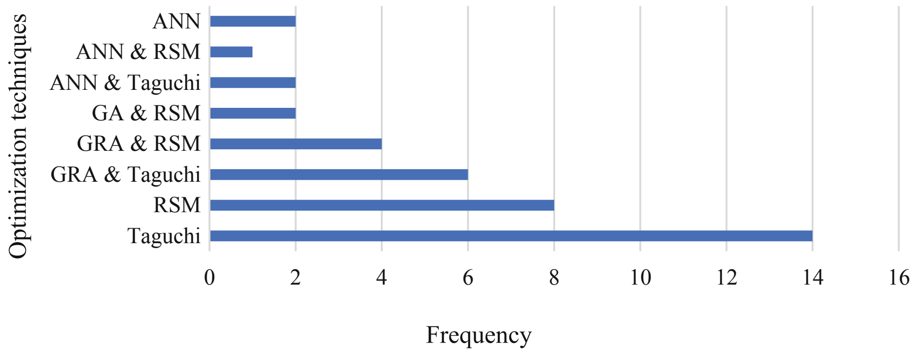

Fig. 8. Utilization of optimization techniques for welding of 6061 AA materials

Grounded on the above table and figure, scholars frequently used Taguchi and RSM tools respectively, to optimize a single response for 6061 AA materials. On the other hand, they used GRA, ANN, and GA for multi-objective response optimization (Fig. 8).

5 Conclusions

In this review research, process parameters of AA 6061 material optimization methods are extensively studied and summarized for further utilization. Based on the reviews the following conclusions are drawn out:

- Friction stir welding is significantly affected by choice of control process parameters. Hence, as a first step of optimization process sorting and selection of these possible process parameters are very crucial. They impart maximum hardness and tensile strength because the lower traverse speed and higher rotational speed, tilt angle, and axial forces are produced adequate heat for joining the base metal.
- Most of the researchers frequently used Taguchi and RSM optimization techniques respectively, to optimize welding parameters for 6061 AA materials. However, the Taguchi method is only used for mono objective responses. Correspondingly, RSM is used for complex optimization calculation processes, but it is suitable for the number of independent variables that are less than three. However, Taguchi and RSM techniques are simple and suitable to optimize *single responses.*
- ANN and GA are given dynamic results due to its biological approach algorithms but it's complicated and long processes related to Taguchi and RSM.
- Grey relational analysis and genetic algorithm coupled with Taguchi, RSM and ANN optimization techniques are preferable for *multi-objective response* optimization.

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