Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 7, July, 2021:1120 – 1135

Applications of numerical approaches for friction stir welding process optimization

Gaurav V. Patel [a], Dr. Neeraj K. Chavda [b], Dr. Manish Mehta[c], Dr. Amit Arora[d]

[a] Research Scholar, Mechanical Engineering, Gujarat Technological University, Ahmedabad, ergvpatel@gmail.com
[b] Associate Professor, Research Supervisor, Mechanical Engineering, GTU, Ahmedabad, neeraj_chavda@yahoo.com
[c] Associate Professor, Department of Mechanical Engineering, Dr. Jivraj Mehta Institute of Technology, Anand, manishmehta@djmit.ac.in
[d] Assistant Professor, Department of Materials Engineering, Indian Institute of Technology, Gandhinagar, amitarora@iitgn.ac.in

Abstract

FSW (Friction stir welding) is a sort of a solid-state joining process in which a non-consumable tool is used to join analogous or divergent materials. The input parameters like TRS (tool rotational speed), welding velocity, axial force of FSW play an extremely indispensable role in obtaining the weld joint quality. The quality of weld joint can be interpreted considering weld macrographs and mechanical properties like tensile strength, hardness, etc. Various traditional and advanced optimization methods are applied with an objective of gaining a virtuous weld-joint with the anticipated mechanical properties. Nowadays, advanced optimization methods like Neuro-Fuzzy, ANN, etc. are utilized to envisage the optimal process parameters of FSW. The prediction of optimal process conditions in welding processes, results into desired weld joint quality. A detailed survey of the utilization of these approaches in the domain of FSW process parameters optimization and prediction to enhance mechanical properties of the friction stir welded joints has been introduced herein.

Keywords: Friction stir welding; Process parameters optimization; Statistical methods; Metaheuristic Algorithms; Predictive methods.

1. Introduction

FSW (Friction stir welding) is evolving as the utmost significant solid-state welding processes used for soft metals like aluminium alloys as it evades several of the general issues of fusion welding [1], with vast utilization in numerous production segments such as automotive, aerospace and shipbuilding. [2] The independent input parameters in FSW include tool, shoulder diameter, work-piece and tool material, tool rotational speed, plunge depth, welding speed, etc [3]. With an intension to get rid of this issue, numerous optimization methods are implemented to identify input parameters for desired output through numerical approaches to stipulate the association among the input and output process parameters [4]. Several input parameters and tool design affect the strength of weld joint. Newer algorithms of advanced optimization methods provide a fruitful methodology to predict weld joint properties with diverse parameters and also offer hypothetical optimal designs as discussed herewith at length.

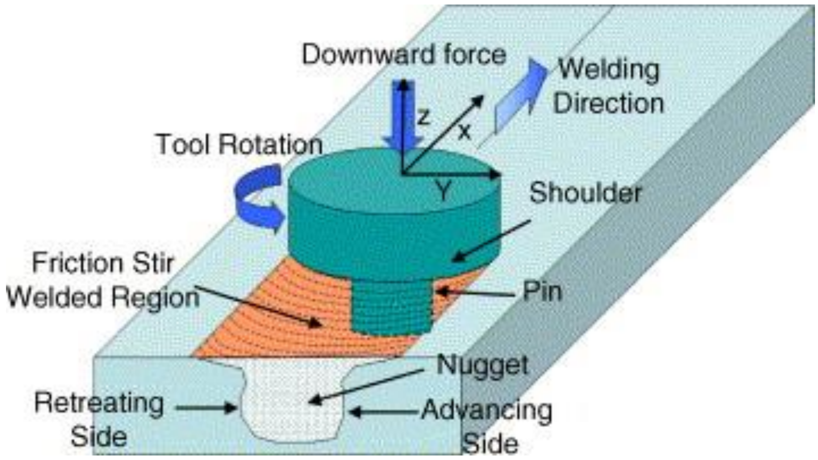

Figure 1. Schematic drawing of FSW process

(Source: R. S. Mishra, Z. Y. Ma, Materials Science and Engg., Reports: A Review Journal, R-50, 2005, pp 1–78)

2. Numerical Approaches

2.1. Optimization Methods

Optimization is an essential part of any engineering process. Numerous methods of optimization are applied to identify input parameters of FSW process for achieving optimum output by constructing mathematical models establishing the correlation among input and output process parameters [5].

DoE (Design of Experiments), Taguchi and ANOVA methodologies are being extensively utilized to perform process parameters optimization since the last two decades. Likewise, RSM (Response Surface Methodology) is utilised to predict output parameters. Presently, metamorphic algorithms like GA (Genetic Algorithm), SA (Simulated annealing), PSO (Particle Swarm Optimization), Fuzzy optimization and computational networks like ANN (Artificial Neural Network) have also emerged swiftly and been appended for several applications in this area.

Application of the above methods to analyse various friction stir welding process parameters has been depicted herewith.

2.1.1. Statistical Methods

•Taguchi and ANOVA:

Taguchi approach is useful to evaluate the utmost dominant process parameters which would obtain improved tensile strength. In this optimization approach, Taguchi parametric design is applied for recognizing various optimum process parameters like tool traverse speed, TRS and axial force to achieve maximum tensile strength of RDE-40 AA alloy joined by FSW process [6]. The consequence of important parameters like welding speed, TRS, tilt angle and pin geometry of FSW tool on lap shear joint strength of polypropylene (PP) composite plates with 20 wt% glass fiber is investigated by means of Taguchi method of design of experiments. It has been observed that the TRS is the utmost influencing parameter while tilt angle is the parameter that affects the lap shear strength the minimum [7].

Taguchi L9 orthogonal array is also applied for lap joined Al–Mg and CuZn34 [7], 6063 and 7075 alloys [8], aluminium alloy AA5083 [9], aluminium alloy 5083-H321[10], AA6351–AA5083 alloys [11], aluminium alloy AA2219 (Al–Cu–Mg alloy) [12], Aluminium alloy AA6061[13], AA1100 [14], aluminium 5052 and 6061 alloy materials [15], surface modified 60/40 brass plates [16], dissimilar Mg alloy plates ZM21 and AZ31 [17], AA 6063 [18], 5052-H34 [19], armour grade AA7075-T651 aluminum Metal Matrix Nano Composites (MMNCs) [20], AA6082-T6 aluminium alloy [21], AM20 magnesium alloy [22], aluminium alloy HE 30 and HE 9 [23], AA6061-T651 and AA7075-T651 aluminum alloys [24], PP composite sheets with 20 wt% carbon fiber [25], AA5754-H22 and AA2024-T3 aluminum alloys [26], Glass Fiber Reinforced Polymer (GFRP) plates [27], 5086 aluminum plates [28], AA5754-H22 and AA5052-H32 sheet metals [29], AZ31B [30], AA2024-T6 and AA6351-T6 [31], aluminium alloy AA2024-T351 [32], Al-B4C Discontinuous reinforced metal matrix (DRMM) [33], Ferritic Stainless steel AISI409 [34], Al6061-Al7075 alloys [35] using friction stir welding. By utilization of ANOVA, authors have reported that the TRS is the furthermost overriding parameter in deciding soundness of FSW weld joint. Rise in the tool rotational speed at steady tool traverse speeds can result to an enhancement of the tensile shear strength to peak, and then a descend [36].

Taguchi experimental design technique is also used to derived the utmost persuasive controlling parameters of Friction Stir Processing like tool travel speed, TRS, tilt angle and penetration depth on the hardness value of Mg alloy. In addition, ANOVA technique indicates that tilt angle, rotational and travel speed are most important parameters influencing the value of hardness [37].

Moreover, Taguchi L27 orthogonal DoE is also utilized to obtain the optimized welding parameters of AZ91 alloy sheets using FSW. The TRS, TTS, penetration depth, pin diameter and shape, shoulder diameter, tilt angle and shoulder concave angle are considered. Optimum process parameters can be achieved with respect to hardness, grain size, yield strength and UTS of the joint. ANOVA (Analysis of Variance) reveals that the TTS is an influential feature in order to determine the mechanical properties of the joint like hardness; diameter of shoulder, pin shape of tool, grain size and TRS are the second to fourth operative parameters [38]. Much consideration desires to be consigned on the TRS as it subsidizes the topmost to the mechanical properties [39].

A systematic review for assessing the machining characteristics of WEDM (Wire Cut Electrical Discharge Machining) [40], AA6082/AA5754 aluminum alloys [41] by means of Taguchi and GRA based multi-objective optimization is also performed. ANOVA is also accomplished additionally to estimate the consequence of apiece design parameter on output parameters [42]. Optimization of FSSW (friction stir spot weld) process parameters of Al5083 and C10100 joints [43], AA8011 [44], composites (AA7010–SiC–Al2O3) [45], non-heat-treatable AA3003-H12 alloy sheets by FSSW [46], Aluminium Matrix Composites (AMCs) [47], AA6061-T651 and AA7075-T651 aluminium alloys [48], AA6061-aluminium alloy (Al-Mg-Si alloy) [49], plasma sprayed Fly ash - Titania composite coating [50], AA7075-T6 aluminum alloy [51] were assessed using ANOVA method. Regression analysis is applied for expansion of experimental correlation [52].

Table 1. Applications of Taguchi & ANOVA techniques to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
S. Prasath, S.Vijayan, S.R.K. Rao (2016)	ZM 21 - AZ 31	M2 tool steel	N = 1700 - 2100 $r.min^{-1}$ TPP = HX, SQ, TCy F = 3 – 4	The profile of tool pin plays a vigorous part but the axial force hardly affects the response.
R Palanivel, RF Laubscher, S Vigneshwaran, I Dinaharan (2016)	AA6351–AA5083	D2 tool steel (oil hardened)	SP = PI, FI, FS N = 800 - 1200 $r.min^{-1}$ T = 45 - 75 $mm.min^{-1}$	The tool shoulder profile, welding as well as TRS have a remarkable consequence on the formation of defect and the size of weld grain.
Jitender Kundu & Hari Singh (2016)	AA 5083-H321	Tool steel H-13	N = 500 - 1400 $r.min^{-1}$ T = 16 - 40 $mm.min^{-1}$ $\theta = 1^\circ - 3^\circ$	Complex optimization of multi-response complications can be effortlessly abridged through Taguchi-based GRA.
Karwande A.H. and S.S. Rao (2016)	AZ31	H13 steel	N = 1000 - 1400 $r.min^{-1}$ T = 60 - 80 $mm.min^{-1}$ M = AZ31, AZ91	The microstructure analysis in the welded joint indicates that the material is properly mixed and there are no pores and having good quality of welding.
Anil Kumar K. S., Anup S. Karur, Shravan Chipli, Ankith Singh (2015)	AA2024-T351	high speed steel (HSS)	N = 355 - 900 $r.min^{-1}$ T = 12.5 - 20 $mm.min^{-1}$ $\theta = 0^\circ - 2^\circ$	The impact of welding speed, tool tilt angle and TRS on joint quality in 2024-T351 aluminum alloy is significant.

P. Asadi, M. Akbari, M K B Givi, M S Panahi (2015)	AZ91	2344 hot working steel	N = 710 - 1400 $r.min^{-1}$ T = 12 - 63 $mm.min^{-1}$ SD = 18 – 22, PD = 4 - 6 PeD = 0.4 - 0.6 θ = 2˚ - 6˚, φ = 3 - 9 G = 1, 2, 3	The process parameters such as the TRS, TTS, pin shape, diameter of tool pin, tilt angle, penetration depth, SD (shoulder diameter) and concave angle of shoulder were considered to determine the hardness, grain size, Yield Strength and UTS.
D. Ahmadkhaniha, A. Zarei-Hanzaki, M. H Sohi, S.M. Bayazid, M. Saba (2015)	FSPed Mg	H13 tool steel	N = 1000 - 1600 $r.min^{-1}$ T = 25 - 63 $mm.min^{-1}$ θ = 1.5˚ - 3˚ PeD = 0.1 - 0.3	Tilt angle, TRS and TTS (tool travel speed) having a substantial effect on stiffness value of FSPed Mg.
S. M. Bayazid, H. Farhangi, A. Ghahramania (2015)	6063-7075 Aluminum alloys	H13 tool steel	N = 800 - 1600 $r.min^{-1}$ T = 80 - 160 $mm.min^{-1}$ L (AS/RS) = AS-7075, AS-6063	TRS and TTS as well as plates' situation parameters have an impact on the tensile strength of joint.
M H Shojaeefard, A Khalkhali, Mostafa Akbari, Mojtaba Tahani (2013)	Al–Mg and CuZn34 alloys	2436 steel alloy	N = 900 - 1400 $r.min^{-1}$ T = 6.25 - 25 $mm.min^{-1}$ θ = 0.5˚ - 2.5˚	Augmenting the TRS at fixed traverse speeds results in an increase in tensile shear force to its maximum value.
Hedi Ahmadi, Mostafa Arab, Faramarz Ashenai Nasrollah Bani Ghasemi (2012)	PP composite with 20 wt% GF	high speed steel	N = 630 - 1250 $r.min^{-1}$ T = 12 - 25 $mm.min^{-1}$ θ = 0˚ - 2˚ G = 1, 2, 3, 4	Threaded cylindrical-conical tool was the best tool for producing higher strength welds. Rotational speed is the utmost noteworthy parameter whereas tilt angle is the least important one.

2.1.2. Metaheuristic Algorithms:

•Genetic Algorithm (GA):

GA is utilized to explore the choices of TRS, TTS, shoulder diameter and pin diameter [53]. Furthermore, against a fixed TRS, a higher welding speed results, in general, to somewhat more residual stress in the tension zone, while a fixed welding speed for a higher rotational speed produces slightly lower value of maximum residual stress [54].

Parameter optimization of tool rotational and travel speed as well as tilt angle of FSW of cryorolled AA2219 alloy [55], AA7075 alloy [56], AA5083-H116 and AA7075-T6 aluminum alloys [57], AA 5052 and AISI 304 [58] is also carried out using GA to achieve sound weld joint with ultimate weld strength and properties like elongation, tensile hardness, tensile strength are made to gain their peak values and the rate of expended electrical energy is curtailed. Moreover, the heat input rate of tool and the backing plate heat loss is also optimized through GA [59].

Table 2. Applications of GA technique to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
M Abbasi, A Abdollahzadeh, H Omidvar, B Bagheri, M Rezaei (2016)	AZ31 Mg alloy	H13 hot work tool steel	N = 500 - 1450 $r.min^{-1}$ T = 15 - 175 $mm.min^{-1}$ θ = 0 - 3˚	Stirring of the material during FSW decreases the grain size, and the decrease is greater with the addition of SiC hard particles.

M Saeidi, G Faraji, M K B Givi, B Manafi, (2015)	AA5083, AA7075	hot-work H13 steel	N = 500 - 800 r.min^{-1} T = 30 - 50 mm.min^{-1}	Traditional mathematical modelling offered a moral forecast of correlation among the studied FSW process parameters and the UTS of the welds.
Q Zhang, G Panoutsos, M Mahfouf, X Liu, K Beamish (2015)	AA5083-O	MX-Triflute	N = 280 - 580 r.min^{-1} T = 0.6 - 1.4 mm.rev^{-1}	By employing an appropriate design among the modest alternatives, it is empower to attain the superlative value in welding productivity, cost competence as well as process reliability.
R. Padmanaban, Muthukumaran V, Vighnesh (2015)	AA1100	tool steel	N = 750 - 1350 r.min^{-1} T = 30 - 90 mm.min^{-1} SD = 12 - 24 mm PD = 4 - 8 mm	FSW process parameters considered and geometry of FSW tool affects the tensile strength of joints.
C. C. Tutum, J. H. Hattel (2010)	--	--	N = 200 - 1000 r.min^{-1} T = 2 - 10 mm.s^{-1}	The foremost attention is on determining an approach to optimize variables, i.e. welding speed and TRS for numerous aims under process related limitations.
Z Meng, H Chen, X Yue (2006)	Aluminum - lithium alloy	--	T = 20 - 80 mm.min^{-1} SD = 13 - 16 mm PD = 3 - 5 mm	The characteristic of genetic algorithm such as easy fulfilling, unrelated problems and overall convergent is making its practicability and application potential extensive.

•Simulated Annealing Algorithm (SA):

Simulated annealing algorithm is used for the experimental examination, parametric optimization and modelling of FSW process to make the enhanced mechanical properties of AA7075 alloy [60] and Polypropylene plates [61] joints. The process parameters considered are TRS and TTS along with axial force. Moreover, mathematical model by means of RSM is also developed to forecast the corrosion resistance of AA2219 alloy by counting FSW process parameters and the mathematical model so obtained is optimized with the help of simulated annealing technique in order to increase corrosion resistance of the AA2219 aluminium alloy joints achieved with FSW [62]. The authors reported significant consequence of the pin shape on the corrosion properties as well as structure of joint.

•Particle Swarm Optimization (PSO):

PSO algorithm is employed to forecast tensile strength of 6061 aluminum alloy. Several factors effect on convergence speed and accuracy including population size, learning factor, inertia weight, fitness function and the type of error. Finally, the particle swarm optimization algorithm has a good potential to use in mechanical and material engineering problems [63].

Table 3. Applications of SA and PSO techniques to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
Simulated Annealing (SA)				
D. Ahmadkhaniha, S.M. Bayazid, M. H Sohi, M. Saba A. Zarei-Hanzaki, (2015)	FSPed Mg	H13 tool steel	N = 1000 - 1600 $r.min^{-1}$ T = 25 - 63 $mm.min^{-1}$ θ = 1.5˚ - 3˚ PeD = 0.1 - 0.3	Tilt angle, TRS and TTS have the utmost noteworthy outcome on FSPed Mg hardness.
S. M. Bayazid, H. Farhangi, A. Ghahramania (2015)	6063-7075 Aluminum alloys	H13 steel	N = 800 - 1600 $r.min^{-1}$ T = 80 - 160 $mm.min^{-1}$ L (AS/RS) = AS-7075, AS-6063	TRS and TTS as well as position parameters of plates have an impact on the tensile strength of weld joint.
M H Shojaeefard, M Akbari, A Khalkhali, M Tahani (2013)	Al–Mg and CuZn34 alloys	2436 steel alloy	N = 900 - 1400 $r.min^{-1}$ T = 6.25 - 25 $mm.min^{-1}$ θ = 0.5˚ - 2.5˚	Augmenting the TRS at continual traverse speeds results in a rise in tensile shear force to its maximum value.
H Ahmadi, F A Ghasemi, N B M Arab, (2012)	PP composite with 20 wt% GF	high speed steel	N = 630 - 1250 $r.min^{-1}$ T = 12 - 25 $mm.min^{-1}$ θ = 0˚ - 2˚ G = 1, 2, 3, 4	Threaded cylindrical-conical tool was the best tool for producing higher strength welds. Rotational speed is the utmost substantial parameter while tilt angle is the least important one.
Particle Swarm Optimization (PSO)				
M Eskandari, B Mirzakhani, M Mansourinejad (2013)	AA6061 aluminium alloy	--	--	PSO algorithm has a good potential to use in mechanical and materials engineering problems. The comparison of stress data of model with experimental results indicated a good agreement.
M H Shojaeefard, M Akbari, M K B Givi, R A Behnagh F Farhani (2013)	AA7075/AA5083	--	--	A hybrid multi-objective evolutionary algorithm is proposed consisting two stages: formulation of a Pareto set by MOPSO & used TOPSIS to acquire the finest result from the Pareto set.

•Fuzzy Algorithm:

In order to attain a wide-ranging knowledge about the influences of process situations on welded materials characterisations, FHMO-FM, a system modelling framework, in the interior of the framework of forecasting multiple properties is applied for the friction stir welded process material, together with mechanical properties, average grain size as well as quality of weld. In the so consequent modelling technique, the multi-objective optimisation method is utilized to expand the correctness as well as understandability characteristics of fuzzy models. A tiered optimisation structure, together with two techniques (NSGA-II and gradient descent), which are also encompassed to increase the modelling effectiveness [64]. A multilevel adaptive fuzzy control method is used for preserving continual friction stir welding power. Multi-level fuzzy method intensely decreases power discrepancies in the existence of noteworthy process turbulences [65].

Table 4. Applications of Fuzzy technique to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
D.Vijayan, V. Seshagiri Rao (2017)	SKD – 61 tool steel	--	N = 1500 - 1900 $r.min^{-1}$ T = 0.5 - 1.5 $mm.min^{-1}$ F = 3 - 9 KN PT = Tape, Sq, Cyl	A regression model was established for the linear terms such as TRS, axial load and TTS by altering shapes of FSW tool pin. There is an enhancement in the values of grey fuzzy reasoning grade compared to grey relational grade.
S. Senthilkumar, M. Boopathi, T C Kanish, A Srivani (2017)	AA6063-T6 aluminum alloy plates	SS316	N = 710 - 1400 $r.min^{-1}$ T = 20 - 80 $mm.min^{-1}$ SPD = 0.2 - 0.4 mm	The presented fuzzy logic scheme possibly will be utilised as a control algorithm for the online monitoring and control of FSW processes within a substantial array of FSW process parameters, with the aim of obtaining decent weldment.
D. Vijayan, V. S Rao (2016)	AA6061 and AA2024 aluminum alloys	H 13	N = 1500 - 1900 $r.min^{-1}$ T = 30 - 90 $mm.min^{-1}$ F = 3 - 9 KN PT = Tape, Sq, Cycle	The ANFIS models are proficient of producing healthier forecasts of tensile properties, such as UTS and TE, compared to the RSM.
B. Parida, S. Pal (2015)	Commercial AA	SS 310	N = 600 - 1500 $r.min^{-1}$ T = 63 - 200 $mm.min^{-1}$ SD = 20 - 35 mm PD = 5 - 8 mm	WS & TG are the utmost significant features influencing the quality of weld. The exactness of the anticipated style can be amended supplementary by cumulative quantity of fuzzy sets.
N M Khansari, N karimi, Dr. M H Sabour (2013)	alloy 2024	HSS tool	N = 800 - 1200 $r.min^{-1}$ T = 50 - 90 $mm.min^{-1}$	Fuzzy logic creates a correlation between input parameters and output data to facilitate the mechanical properties for even unverified rotational speed can be projected.
Q. Zhang, G. Panoutsos, M. Mahfouf, I. Norris, K. Beamish (2012)	AA 5083 aluminum alloys	MX-Triflute tool	N = 280 - 580 $r.min^{-1}$ T = 0.6 - 1.4 $mm.rev^{-1}$	Multi-objective optimization technique improves accuracy and interpretability attributes of fuzzy models
T. A. Davis, P. D. Ngo, Y. C. Shin (2012)	7075-T6 aluminum	--	N = 1500 - 2500 $r.min^{-1}$ P = 225 - 350 W	Quality of FSW weld joint can be enhanced by the control of spindle power.

H Ahmadi, F A Ghasemi, N B M Arab, (2012)	PP composite with 20 wt% GF	high speed steel	N = 630 - 1250 $r.min^{-1}$ T = 12 - 25 $mm.min^{-1}$ $\theta = 0^\circ - 2^\circ$ G = 1, 2, 3, 4	Threaded cylindrical-conical tool was the best tool for producing higher strength welds. Rotational speed is the utmost momentous parameter while tilt angle is the least important one.

Q. Zhang et al. [66], established a novel systematic data driven fuzzy modelling method, considering both the modelling interpretability and accuracy as characteristics. A data driven modelling framework is projected, planned and utilized so as to model the complex FSW behaviours relating to AA5083 alloy, containing of the mechanical properties, grain size along with interior process properties. In the so derivative modelling method, the multi-objective optimisation method is working to increase the correctness as well as interpretability features of fuzzy models. An ordered double loop optimisation construction, together with two techniques (MORSSA and RSSA), which are also involved to augment the modelling efficacy. By knowing the capability of fuzzy logic in creating an intelligent association among the input process parameters and output data, the relationship between the forward and rotational speed as an input and mechanical properties as an output based on experimental data is proposed [67].

ANFIS (Adaptive neuro-fuzzy inference system) is used to improve the tensile properties, as well as the UTS and elongation of FSW age hard enable AA6061 and AA2024 alloys. The influence of the welding process parameters, like the welding speed, TRS, pin profile and axial load on the tensile elongation and UTS are investigated by means of a 3-level, 4-factor Box-Behnken experimental design [68].

2.2. Predictive Methods

2.2.1. Response Surface Methodology (RSM)

An effort is made to establish an experimental connection to forecast the tensile strength of FSW processed AZ31B Mg alloy [69], tensile shear fracture load of FSSW AA2024-T3 AA alloy joints [70], AA5052–LCS (Low Carbon Steel) joints [71], AA5083-H12 and AA6061-T6 [72], [73], AA2014 and AA6061 Aluminium alloys [74], average grain size and tensile strength of FSW weld nugget of AA6061-T6 joints [75], tool traverse speed (S), tool rotational speed (N), axial force (F) and the response parameters such as yield strength, UTS and percentage of elongation of AA6351-T6 and AA6061-T6 alloy [76], resistance spot welded AA2024-T3 joints [77], friction stir welded aluminum alloy AA7075 with SiC reinforcement particle [78], aluminum alloys AA2024-AA7075 [79], AA 2024 and AA6061 aluminum alloys [80], Aluminum material A1100 [81], AZ61A magnesium alloy [82], Al- Mg- Si aluminum alloy [83], AA7075-T6 and AA6061-T6 [84], [85] with the application of RSM by combining process parameters like welding speed, axial force and TRS. The developed relationship is effectually used to forecast tensile strength of FSW joints at the confidence level of 95 %.

Multi-objective Optimization by RSM is a convenient practice to optimize the FSW process parameters to acquire highest tensile strength deprived of fading the corrosion resistance of FSW joints. Tool rotational speed contributes additional on UTS trailed by welding speed & axial force. Optimization of FSSW process parameters for joining AA6061-T6 alloy with AZ31B Mg alloy sheets, AA5083-H12 and AA6061-T6 alloy is also performed to forecast the TSFL combining the four utmost imperative friction stir spot welding parameters, i.e., TRS, plunge rate, DT and TD ratio using RSM technique.

A novel tool-path movement is executed in the FSW of Aluminum alloy AA6061-T6 plates and termed as Friction Stir Weave Welding (FSWW). The intention of the stated innovative procedure is to improve the weld joint quality in accordance to TS and microstructural properties by the assortment of effective process parameters like step-size (tool-path movements), weaving rate and speed of spindle. RSM based Box–Behnken design is also applied to examine the impact of unlike operational situations on mechanical properties of the joints of Nylon-6 plates joined via a innovative method of heat assisted FSW by utilizing an peripheral heat source.

Table 5. Applications of RSM technique to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
M Sundaram, V Balasubramanian (2016)	AA6061 aluminum alloy and AZ31B magnesium alloy	super high speed steel (SHSS)	N = 600 - 1400 $r.min^{-1}$ PR = 8 - 24 $mm.min^{-1}$ DT = 3 - 7 s TDR = 1.5 - 3.5	The TPR (tool plunge rate) have the largest impact on tensile shear fracture load, trailed by TRS, TDR (tool diameter ratio) and DL (dwell time)
S. Siddharth, T. Senthilkumar (2016)	Al 5083 and C 10100 Joints	H13 tool steel	N = 800 - 1600 $r.min^{-1}$ DT = 11 - 15 s PlD = 1.4 - 2.2 mm	Three vital process parameters like DL, PD (plunge depth) and TRS influence the quality of joints.
G. Elatharasan, V.S. Senthil Kumar (2013)	AA6061-T6	--	N = 800 - 1200 $r.min^{-1}$ T = 30 - 90 $mm.min^{-1}$ F = 6 - 10 kN	Yield strength and UTS of the FSW joints improved with the growth in welding speed, TRS and AF up to a highest value and then declined. Trailing Edge of joints amplified upon increment in TRS and AF, but decreased by growing of speed of welding, endlessly.
R. Palanivel, P. Koshy Mathews (2012)	AA5083H111 aluminum alloy	High carbon high chromium steel	N = 500 - 1500 $r.min^{-1}$ T = 30 - 108 $mm.min^{-1}$ F = 0.86 - 1.80 t	A mathematical model is established for designing a set of experimentations, scrutinizing the optimum amalgamation of input variables and articulating the values in graphical form, Response Surface Method is utmost fruitful technique.
S. Rajakumar , C. Muralidharan, V. Balasubramanian (2011)	AA6061-T6 aluminium alloy	high carbon steel	N = 862 - 1337 $r.min^{-1}$ T = 32.43 $mm.min^{-1}$ - 127.5 $mm.min^{-1}$ F = 5.62 - 10.37 KN SD = 7.86 - 22.13 mm PD = 2.62 - 7.37 mm THrd = 243 - 956 N	The welding speed is the furthermost principal welding parameter and its collaboration with the TRS should be supervised.
G Padmanaban, V Balasubramanian (2010)	AZ31B Magnesium Alloy	high carbon steel	N = 1400 - 1800 $r.min^{-1}$ T = 0.37 - 1.25 $mm.s^{-1}$ F = 2 - 4 KN	TRS has the superior impact on TS, trailed by welding speed and then lastly axial force.
R. Karthikeyan V. Balasubramanian (2010)	AA2024 aluminum alloy	high-carbon steel	N = 600 - 1400 $r.min^{-1}$ T = 4 - 20 $mm.min^{-1}$ Pl. D = 2 - 4 KN DT = 3 - 7 s	The plunge rate has superior effect on TSFL (tensile shear fracture load) trailed by PD, DT and TRS.
S. Rajakumar, C. Muralidharan, V. Balasubramanian (2010)	AA 6061-T6 alloy	high carbon steel	N = 924 - 1875 $r.min^{-1}$ T = 12.43 $mm.min^{-1}$ - 107.56 $mm.min^{-1}$ F = 5.62 - 10.37 KN SD = 7.86 - 22.13 mm PD = 2.62 - 7.37 mm THrd = 243 - 956 N	The established correlations can be efficiently applied to forecast the grain size and tensile strength of FSW processed aluminium alloy joints within the range of parameters.

2.2.2. Artificial Neural Network (ANN)

ANN is used for the mechanical property calculation of welded Aluminum plates, friction stir welded AA7075-O to AA5083-O alloys, AA8014, AA-7075-T6, AA5754 H111 aluminum plates using FSW method. So as to deal with the problem of multi-objective optimization, an advanced hybrid multi-objective algorithm is used. This technique is used to attain the adaptable parameters of a model further efficiently than the traditional trial & error style, particularly where multifaceted boundary conditions are executed.

Table 6. Applications of ANN technique to FSW Process

Authors	Base Material Used	Tool Material	Process Parameters	Remarks
V M Dehabadi, S Ghorbanpour, G Azimi (2016)	Aluminum 6061 alloy	H13 Steel	N = 1000 $r.min^{-1}$ T = 28 $mm.min^{-1}$ θ = 3˚ PT = Threadless, Threaded ST = Flat, Conical	Applying mathematical modeling methods such as ANN can save time, costs and material that consequences in optimized designs.
M.Muthu Krishnan, R. Deepak, J. Maniraj, K. Anganan (2016)	Aluminium alloys AA6063 and A319	HSS (Hardened)	N = 800 - 1300 $r.min^{-1}$ T = 20 - 40 $mm.min^{-1}$ F = 3 - 8 KN	The upsurge in TRS and axial load upsurges the responses to a convinced level and decreases after reaching a maximum value.
E Maleki (2015)	7075-T6 aluminum alloy	--	N = 900 - 1800 $r.min^{-1}$ T = 20 - 100 $mm.min^{-1}$ F = 6 - 10 KN PD = 3 - 7 mm THd = 33 - 56 HRc	Four operative parameters of FSW process include: yield strength, TS, notch-tensile strength and hardness of welding zone modeled.
C Patel, S Das, R G Narayanan (2014)	Al 6061-T651 sheets plates	--	N = 1200 - 1800 $r.min^{-1}$ T = 50 - 110 $mm.min^{-1}$ F = 5 - 11 KN SD = 10 - 22 mm	CAFE model generated data can be utilized to train and establish an accurate ANN model for prediction purposes.
N. D. Ghetiya, K.M. Patel (2014)	aluminium alloy AA8014	H13	N = 355 - 2000 $r.min^{-1}$ T = 20 - 63 $mm.min^{-1}$ F = 1 - 5 KN SD = 16 - 24 mm	For the given FSW process parameters, the TS of friction stir welded AA plate can be prophesied utilizing the developed neural network.
H. Wang, J. dos Santos, P. A. Colegrove, (2013)	7449-T7 aluminium alloy	H13	N = 1300 $r.min^{-1}$ T = 2 - 8 mm s^{-1} θ = 3˚	A hybrid model of FSW was constructed by coalescing a progression model with an ANN model and utilized to examine the thermal boundary conditions at the edge among backing bar and the workpiece.
Y. K. Yousif, B. I. Kazem, K. M. Daws (2008)	Hot Rolled AA	--	N =710, 900, 1400 $r.min^{-1}$ T = 70,40 and 140 $mm.min^{-1}$ PD = 2 mm	Relationships between measured and predicted values of TS, bending stress are better than those of elongation.
H Okuyucu , E Arcaklioglu, A Kurt, (2005)	Hot Rolled AA	--	N = 500 - 1500 $r.min^{-1}$ T = 6.25 - 20 $mm.min^{-1}$ F = 210 KN	Neural networks can be used for the computation of mechanical properties of friction stir welded Aluminum plates.

A hybrid model CAFEANN (Cellular Automata Finite Element–Artificial Neural Network) is implemented to envisage the progression of grain size and yield strength throughout FSW process. Thus, ANN is utilized as a ‘virtual machine’ to investigate the influence of TRS, TTS, axial force and SD on the dissimilarity in grain size and yield strength. ANN is applied for modelling of FSW effective parameters. ANN (Artificial Neural

Network) method is utilized to forecast the micro-hardness of FSW processed AA6061 alloy plates. Thus, the correctness of neural networks modelling is entirely analogous with the precision accomplished by more conventional modelling structures.

In order to simulate the intelligent supervisory competence of human beings, GONNS (genetically optimized neural network) systems is established. Upon being trained with investigational observations or data, GONNS utilizes single or multiple ANN to characterize complicated systems. One or more genetic algorithms are utilized for the optimization.

3. Concluding Remarks

The establishment of thorough weld joints between analogous or diverse materials is of boundless consequence in FSW process. One of the greatest stimulating complications is electing apposite welding parameters to facilitate manufacturing decent weld joint. Present day, the RSM and ANN are widely utilized to formulate model for FSW, predicting the association between FSW process parameters and weld properties. Merging with the advanced optimization methods like GA, SA, Fuzzy optimization and PSO, ANN gives tremendous prediction accuracy. ANN for envisaging belongings of friction stir welded plates is well established hence, providing a scope for adoption of a new advanced methodology in this area such as machine learning and deep learning.

References

[1] Rai R., De A., Bhadeshia H. K. D. H. and DebRoy T. (2011). Review: friction stir welding tools, Science and Technology of Welding and Joining, vol 16, issue 4, 325-342.

[2] Zhang, H., Lin, S. B., Wu, L., Feng, J. C., and Guo, H. P. (2003). Microstructure of friction stir welds in AZ31 magnesium alloy. Chin. J. Nonferrous. Metals, 13(6), 1510-1513.

[3] Shahi P., Barmouz M., Asadi P. (2014). Force and torque in friction stir welding, Advances in Friction Stir Welding and Processing, 459-498.

[4] Benyounis K. Y., Olabi A. G., (2008). Optimization of different welding processes using statistical and numerical approaches- A reference guide, Advances in Engineering Software, 39(6), 483-496

[5] Tutum C.C., Hattel J.H. (2011) Numerical optimisation of friction stir welding: Review of future challenges, Journal of Science and Technology of Welding and Joining, 16(4), 318-324.

[6] Lakshminarayanan A. K., Balasubramanian V. (2008). Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique, Trans of Non-Ferrous Metals Society of China, 18, 548-554.

[7] Shojaeefard M. H., Khalkhali A., Akbari M., Tahani M. (2013). Application of Taguchi optimization technique in determining aluminum to brass friction stir welding parameters, Materials and Design, 52, 587-592.

[8] Bayazid S. M., Farhangi H., Ghahramani A. (2015). Investigation of friction stir welding parameters of 6063-7075 Aluminum alloys by Taguchi method, 5th International Biennial Conference on Ultrafine Grained and Nanostructured Materials (UFGNSM15), Procedia Materials Science, 11, 6-11.

[9] Chien C.-H., Lin W.-B., Chen T. (2011) Optimal FSW process parameters for aluminum alloys AA5083", Journal of the Chinese Institute of Engineers, 34(1), 99-105.

[10] Roshan S. B., Jooibari M. B., Teimouri R., Asgharzadeh-Ahmadi G., Falahati-Naghibi M., Sohrabpoor H. (2013). Optimization of friction stir welding process of AA7075 aluminum alloy to achieve desirable mechanical properties using ANFIS models and simulated annealing algorithm, International Journal on Advanced Manufacturing Technology, 69, 1803-1818.

[11] Jaiganesh V., Maruthu B., Gopinath E. (2014). Optimization of process parameters on friction stir welding of high-density polypropylene plate, 12th Global Congress on Manufacturing and Management (GCMM2014), Procedia Engineering, 97, 1957-1965.

[12] Rambabu G., Naik D. B., Venkata Rao C.H., Rao K. S., Reddy G. M. (2015). Optimization of friction stir welding parameters for improved corrosion resistance of AA2219 aluminum alloy joints, Science Direct, Defence Technology, 11, 330-337.

[13] Manurung Y.H.P., Mohamed M.A., Abidin A.Z. (2017). Structural life enhancement on friction stir welded AA6061 with optimized process and HFMI/PIT parameters, International Journal of Advanced Manufacturing Technology, 90, 3575-3583.

[14] Khalkhali A., Sarmadi M., Sarikhani E. (2017). Investigation on the best process criteria for lap joint friction stir welding of AA1100 aluminum alloy via Taguchi technique and ANOVA, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231(2), 329-342.

[15] Sandeep R., Sudhakara D., Prasanthi G. (2017). Optimization of friction stir welding process parameters to join AL 5052 & AL 6061 alloy plates using grey-Taguchi technique, ASME 2017 12th International Manufacturing Science and Engineering Conference (MSEC 2017).

[16] Meena K., Kumar A., Pandya S.N. (2017). Optimization of Friction Stir Processing Parameters for 60/40 Brass using Taguchi Method, Materials Today: Proceedings, 4(2), 1978-1987.

[17] Prasath S., Vijayan S., Rao S.R.K. (2016). Optimization of Friction Stir welding process parameters for joining ZM 21 to AZ 31 of dissimilar Magnesium alloys using Taguchi technique, Metallurgia Italiana, 108(5), 25-33.

[18] Santhanam S.K.V., Ramaiyan S., Rathinaraj L., Chandran R. (2016). Multi response optimization of submerged friction stir welding process parameters using grey relational analysis, ASME 2016 International Mechanical Engineering Congress and Exposition (IMECE-2016).

[19] Radj B.M., Senthilvelan T. (2016). Statistical analysis of friction stir welded AA 5052-H34 weldments by applying Taguchi technique, ARPN Journal of Engineering and Applied Sciences, 11(18), 11062-11067.

[20] Vigneshwar M., Divagar S., Selvamani S.T. (2016). Mechanical and Metallurgical Behavior of Friction welded Dual Nano Particles Reinforced Armour Grade Al based Nanocomposite joints in optimized Condition, Materials Today: Proceedings, 3(10), 3740-3745.

[21] Silva A.C.F., Braga D.F.O., de Figueiredo M.A.V., Moreira P.M.G.P. (2015). Ultimate tensile strength optimization of different FSW aluminium alloy joints, International Journal of Advanced Manufacturing Technology, 79, 805-814.

[22] Sahu P.K., Pal S. (2015). Multi-response optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis, Journal of Magnesium and Alloys, 3(1), 36-46.

[23] Shinde V.R., Sapre M., Jatti V.S. (2015). Optimization of friction stir welding process parameters using taguchi's method, Global Journal of Pure and Applied Mathematics, 11(2), 777-778.

[24] Ravikumar S., Achuth Chandrasekhar V.S., Barath R.B. (2015). Comparison of factor analysis method with assignment weightage method in optimizing the dissimilar friction stir welding parameters for heat treatable aluminium alloys, International Journal of Applied Engineering Research, 10(13), 11161-11164.

[25] Ahmadi H., Mostafa Arab N.B., Ghasemi F.A. (2014). Optimization of process parameters for friction stir lap welding of carbon fibre reinforced thermoplastic composites by Taguchi method, Journal of Mechanical Science and Technology, 28(1), 279-284.

[26] Bozkurt Y., Bilici M.K. (2014). Taguchi optimization of process parameters in friction stir spot welding of AA5754 and AA2024 alloys, Journal of Advanced Materials Research, 1016, 161-166.

[27] Balamugundan B., Karthikeyan L. (2014). Optimization of process parameters during milling of friction stir processed GFRP composites, Journal of Advanced Materials Research, Vols. 984-985, 297-303.

[28] Javadi Y., Sadeghi S., Najafabadi M.A. (2014). Taguchi optimization and ultrasonic measurement of residual stresses in the friction stir welding, Journal of Materials and Design, 55, 27-34.

[29] Kesharwani R.K., Panda S.K., Pal S.K. (2014). Experimental Investigations on Formability of Aluminum Tailor Friction Stir Welded Blanks in Deep Drawing Process, Journal of Materials Engineering and Performance, 24(2), 1038-1049.

[30] Kumar R., Pragash M.S., Varghese S. (2013) Optimizing the process parameters of FSW on AZ31B Mg alloy by Taguchi-grey method, Middle East Journal of Scientific Research, 15(1), 161-167.

[31] Murali Krishna P., Ramanaiah N., Prasada Rao K. (2013). Optimization of process parameters for friction Stir welding of dissimilar Aluminum alloys (AA2024-T6 and AA6351-T6) by using Taguchi method, International Journal of Industrial Engineering Computations, 4(1), 71-80.

[32] Vidal C., Infante V., Vilaa P. (2010). Assessment of improvement techniques effect on fatigue behaviour of friction stir welded aerospace aluminium alloys, Procedia Engineering, 2(1), 1605-1616.

[33] Venkatesha C., Arun N. M., Venkatesan R. (2014)., 12th Global Congress on Manufacturing and Management (GCMM 2014), Procedia Engineering, 97, 975-985.

[34] Ghosh N., Rudrapati R., Pal P. K., Nandi G. (2017). Parametric Optimization of Gas Metal Arc Welding process by using Taguchi method on Ferritic Stainless steel AISI409, 5th International Conference of Materials Processing and Characterization (ICMPC 2016), Materials Today: Proceedings, 4, 2213-2221.

[35] Ugrasen G., Bharath G., Kishor Kumar G., Sagar R., Shivu P R., Keshavamurthy R. (2018). Optimization of process parameters for Al6061-Al7075 alloys in friction stir welding usinf Taguchi's technique, Materials Today: Proceedings, 5, 3027-3035.

[36] Ahmadi H., Mostafa Arab N. B., Ghasemi F. A. (2012). Application of Taguchi method to optimize friction stir welding parameters for polypropylene composite lap joints, Archives Des Sciences, 65(7), 59-74.

[37] Ahmadkhaniha D., Heydarzadeh Sohi M., Zarei-Hanzaki A., Bayazid S.M., Saba M. (2015). Taguchi optimization of process parameters in friction stir processing of pure Mg, Journal of Magnesium and Alloys, 3, 168-172.

[38] Asadi P., Akbari M., Besharati Givi M. K. and Panahi M. S. Optimization of AZ91 friction stir welding parameters using Taguchi method, Proc IMechE Part L: J Materials: Design and Applications, 230(1).

[39] K. S. Anil Kumar, Karur A. S., Chipli S., Singh A. (2015). Optimization of FSW Parameters to Improve the Mechanical Properties of AA2024-T351 Similar Joints Using Taguchi Method, Journal of Mechanical Engineering and Automation, 5(3B), 27-32.

[40] Thankachan T., Soorya Prakash K., Loganathan M. (2017). WEDM process parameter optimization of FSPed copper-BN composites, Materials and Manufacturing Processes, 33(3), 350-358.

[41] Kasman S. (2013). Multi-response optimization using the Taguchi-based grey relational analysis: A case study for dissimilar friction stir butt welding of AA6082-T6/AA5754-H111, International Journal of Advanced Manufacturing Technology, 68, 795-804.

[42] Anuradha M., Sailaja C., Chittaranjan Das V. (2017). Effect of tool pin profile and optimization of process parameters on A6061 by friction stir welding using Taguchi method, International Journal of Mechanical Engineering and Technology, 8(6), 615-621.

[43] Siddharth S. and Senthilkumar T. (2016). Optimization of Friction Stir Spot Welding Process Parameters of Dissimilar Al 5083 and C 10100 Joints Using Response Surface Methodology, Russian Journal of Non-Ferrous Metals, 57(5), 456–466. ©Allerton Press, Inc., 2016.

[44] Ghetiya N.D., Patel K.M., Kavar A.J. (2016). Multi-objective Optimization of FSW Process Parameters of Aluminium Alloy Using Taguchi-Based Grey Relational Analysis, Transactions of the Indian Institute of Metals, 69(4), 917-923.

[45] Gopi Krishnan P., Siva K. (2016). Taguchi optimization of process parameters in friction stir welding of the AA7010–SiC–Al2O3 hybrid composite, Journal of High Temperature Material Processes, 20(3), 185-196.

[46] Tutar M., Aydin H., Yuce C., Yavuz N., Bayram A. (2014). The optimisation of process parameters for friction stir spot-welded AA3003-H12 aluminium alloy using a Taguchi orthogonal array, Journal of Materials and Design, 63, 789-797.

[47] Ashok Kumar B., Murugan N. (2014). Optimization of friction stir welding process parameters to maximize tensile strength of stir cast AA6061-T6/AlNp composite, Journal of Materials and Design, 57, 383-393.

[48] Kumar S.R., Rao V.S., Pranesh V. (2014). Multiple response optimization with grey relational analysis of friction stir welding parameters in joining dissimilar aluminium alloys by Taguchi method", Journal of Applied Mechanics and Materials, Vols. 592-594, 555-559.

[49] Rajakumar S., Muralidharan C., Balasubramanian V. (2011). Response surfaces and sensitivity analysis for friction stir welded AA6061-T6 aluminium alloy joints, International Journal of Manufacturing Research, 6(3), 215-235.

[50] Sunil J. R., Keshavamurthy R., Prakash C. P. S., Channabasappa B. H. (2015). Optimization of Process Parameters for Plasma Sprayed Flyash-Titania Composite Coatings, 4th International Conference on Materials Processing and Characterization, Materials Today: Proceedings, 2, 2482 – 2490.

[51] Lotfi A. H. & Nourouzi S. (2014). Predictions of the optimized friction stir welding process parameters for joining AA7075-T6 aluminum alloy using preheating system, International Journal of advanced Manufacturing Technology, 73, 1717-1737.

[52] Tansel I. N., Demetgul M., Okuyucu H., Yapici A. (2010). Optimizations of friction stir welding of aluminum alloy by using genetically optimized neural network", International Journal of Advanced Manufacturing Technology, 48, 95-110.

[53] Padmanaban R., Muthukumaran V. and Vighnesh A. (2015). Parameter Optimization for Friction Stir Welding AA1100, Applied Mechanics and Materials, Vols. 813-814, 462-466.

[54] Tutum C. C. and Hattel J. H. (2010). Optimisation of process parameters in friction stir welding based on residual stress analysis: a feasibility study, Science and Technology of Welding & Joining, 15(5), 369-377.

[55] Kamal Babu K., Panneerselvam K., Sathiya P., Noorul Haq A., Sundarrajan S., Mastanaiah P., Srinivasa Murthy C.V. (2018). Parameter optimization of friction stir welding of cryorolled AA2219 alloy using artificial neural network modeling with genetic algorithm, International Journal of Advanced Manufacturing Technology, 94, 3117-3129.

[56] Hussain G., Ranjbar M., Hassanzadeh S. (2017). Trade-off among mechanical properties and energy consumption in multi-pass friction stir processing of Al7075 alloy employing neural network-based genetic optimization, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(1), 129-139.

[57] Saeidi M., Manafi B., Besharati Givi M.K., Faraji G. (2016). Mathematical modeling and optimization of friction stir welding process parameters in AA5083 and AA7075 aluminum alloy joints, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230(7), 1284-1294.

[58] Darzi Naghibi H., Shakeri M., Hosseinzadeh M. (2016). Neural Network and Genetic Algorithm Based Modeling and Optimization of Tensile Properties in FSW of AA 5052 to AISI 304 Dissimilar Joints, Transactions of the Indian Institute of Metals, 69(4), 891-900.

[59] Zhou X., Pan W., MacKenzie D. (2013). Identifying friction stir welding process parameters through coupled numerical and experimental analysis", International Journal of Pressure Vessels and Piping, Vols.108-109, 2-6.

[60] Kundu J. and Singh H. (2016). Friction stir welding: multi-response optimisation using Taguchi-based GRA, Production & Manufacturing research: an open access Journal, Taylor & Francis, 4(1), 228–241.

[61] Palanivel R, Laubscher RF, Vigneshwaran S and Dinaharan I (2016). Prediction and optimization of the mechanical properties of dissimilar friction stir welding of aluminum alloys using design of experiments, Proc IMechE Part B: J Engineering Manufacture, 232(8), 1–11.

[62] Prasath S., Vijayan S., Rao S.R.K. (2016). Optimization of Friction Stir welding process parameters for joining ZM 21 to AZ 31 of dissimilar Magnesium alloys using Taguchi technique, La Metallurgia Italiana - n.5.

[63] Eskandari M., Mirzakhani B., Mansourinejad M. (2013). Prediction Tensile Stress of AA6061 Using Particle Swarm Optimization Algorithm, International Journal of Engineering Research and Applications (IJERA), 3(3), 243-246.

[64] Zhang Q., Mahfouf M., Panoutsos G., Beamish K., Norris I. (2011). Multiple Characterisation Modelling of Friction Stir Welding Using a Genetic Multi-objective Data-driven Fuzzy Modelling Approach, 2011 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE 2011).

[65] Davis T. A. & Phuong D. Ngo & Shin Y. C. (2012). Multi-level fuzzy control of friction stir welding power, Int J Adv Manufacturing Technolology, 59, 559–567.

[66] Zhang Q., Mahfouf M., Panoutsos G., Beamish K. and Norris I. (2012). Knowledge discovery for friction stir welding via data driven approaches Part 2 – multi objective modelling using fuzzy rule-based systems, Science and Technology of Welding and Joining, 17(8), 681-693.

[67] Khansari N. M., Karimi N., Sabour M. H. (2013). Optimization of friction stir welding by fuzzy logic, 13th Iranian Conference of Fuzzy systems (IFSC2013).

[68] Vijayan D., Seshagiri Rao V. (2016). Parametric optimization of friction stir welding process of age hardenable aluminum alloys–ANFIS modelling, Journal of Central South University, 23(8), 1847-1857.

[69] Padmanaban G. and Balasubramanian V. (2010). Prediction of tensile strength and optimization of process parameters for friction stir welded AZ31B magnesium alloy, Proc. Institution of Mechanical Engineering, Part B: J. Engineering Manufacture, Vol. 224.

[70] Karthikeyan R. and Balasubramanian V. (2010). Predictions of the optimized friction stir spot welding process parameters for joining AA2024 aluminum alloy using RSM, International Journal of Advanced Manufacturing Technology, 51, 173-183.

[71] Piccini J.M., Svoboda H.G. (2017). Tool geometry optimization in friction stir spot welding of Al-steel joints", Journal of Manufacturing Processes, 26, 142-156.

[72] Ghaffarpour M., Kazemi M., Mohammadi Sefat M.J., Aziz A., Dehghani K. (2017) Evaluation of dissimilar joints properties of 5083-H12 and 6061-T6 aluminum alloys produced by tungsten inert gas and friction stir welding, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 231(2), 297-308.

[73] Babu S.R., Karthik P., Karthik S., Kumar S.A., Morris J. (2014). Optimization of process parameters during friction stir welding of dissimilar aluminium alloys (AA 5083 & AA 6061) using Taguchi L9 orthogonal array, Journal of Applied Mechanics and Materials, Vols. 592-594, 630-635.

[74] Hema P., Sai Kumar Naik K., Ravindranath K. (2017). Prediction of Effect of Process Parameters on Friction Stir Welded Joints of dissimilar Aluminium Alloy AA2014 & AA6061 Using Taper Pin Profile, Materials Today: Proceedings, 4(2), 2174-2183.

[75] Rajakumar S., Muralidharan C., Balasubramanian V. (2010). Establishing empirical relationships to predict grain size and tensile strength of friction stir welded AA 6061-T6 aluminium alloy joints, Trans of Non-Ferrous Metals Society of China, 20(10),1863-1872.

[76] Prasanth R.S.S., Hans Raj K. (2017). Determination of Optimal Process Parameters of Friction Stir Welding to Join Dissimilar Aluminum Alloys Using Artificial Bee Colony Algorithm, Transactions of the Indian Institute of Metals, 71, 453–462.

[77] Karthikeyan R., Balasubramaian V., (2017). Optimization of Electrical Resistance Spot Welding and Comparison with Friction Stir Spot Welding of AA2024-T3 Aluminum Alloy Joints, Materials Today: Proceedings, 4(2), 1762-1771.

[78] Deepandurai K., Parameshwaran R. (2016). Multiresponse Optimization of FSW Parameters for Cast AA7075/SiCp Composite, Journal of Materials and Manufacturing Processes, 31(10), 1333-1341.

[79] Padmanaban R., Balusamy V., Saikrishna V., Gopath Niranthar K. (2014). Simulated annealing based parameter optimization for Friction Stir Welding of dissimilar aluminum alloys, Procedia Engineering, 97, 864-870.

[80] Vijayan D., Seshagiri Rao V. (2014). A multi response optimization of tool pin profile on the tensile behavior of age-hardenable aluminum alloys during friction stir welding, Research Journal of Applied Sciences, Engineering and Technology, 7(21), 4503-4518.

[81] Baskoro A.S., Nugroho A.A.D., Rahayu D., Suwarsono, Kiswanto G., Winarto W. (2013). Effects of welding parameters in micro friction stir lap welding of aluminum A1100, Journal of Advanced Materials Research, 789, 356-359.

[82] Rajakumar S., Razalrose A., Balasubramanian V. (2013). Friction stir welding of AZ61A magnesium alloy: A parametric study, International Journal of Advanced Manufacturing Technology, 68, 277-292.

[83] Karthikeyan R., Balasubramanian V. (2012). Optimisation and sensitivity analysis of friction stir spot-welding process parameters for joining AA 6061 aluminum alloy, International Journal of Manufacturing Research, 7(3), 257-272.

[84] Elatharasan G., Senthil Kumar V. S. (2013). An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM, International Conference on Design and Manufacturing (IConDM 2013), Procedia Engineering, 64, 1227-1234.

[85] Elatharasan G., Kumar V.S.S. (2012). Modelling and optimization of friction stir welding parameters for dissimilar aluminium alloys using RSM, Procedia Engineering, 38, 3477-3481.