International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 18 (2019) pp.3668-3677
© Research India Publications. http://www.ripublication.com

Using Multi Criteria Decision Making in Optimizing the Friction Stir Welding Process of Pipes:A Tool Pin Diameter Perspective

A. M. El-Kassas[1], Ibrahim Sabry[2]

[1] *Department of Production Engineering and Mechanical Design, Faculty of Engineering,*
Tanta University, P.O. Box, Tanta 31512, Egypt.
[2] *Manufacturing Engineering Department, Modern Academy for Engineering and Technology,*
P.O. Box Cairo 11571, Egypt.

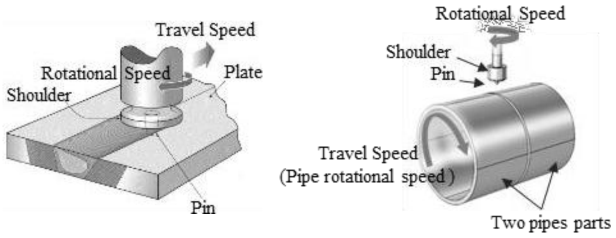
Abstract

This paper is the first to optimize the friction stir welding process of pipes (FSWoP) considering the tool pin diameter effect using the multi criteria decision making (MCDM) techniques. Significant parameters of the FSWoP process have been considered in many optimization studies, however, the effect of the tool pin diameter has been never studied. Experimental work was performed using a new modified fixture to eliminate the post-process problems. Experiments were performed at three levels of three parameters: tool pin diameter tool, rotational speed and travel speed. For optimization, the MCDM methods were applied as an approach for selecting the optimal values of the parameters. Using MCDM in optimizing the FSWoP process is rare and has a limited number of publications. The MCDM techniques used are the Grey Relational Analysis (GRA) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to find the optimum process parameters which maximize the values of responses: the tensile strength and the hardness of the welded joint. The same results were obtained through both techniques and the optimum values for the used parameter ranges were 5 mm, 1800 RPM and 10 mm/min for the pin diameter, rotational speed and travel speed respectively.

Keywords: Friction Stir Welding of Pipes, GRA, Multi Criteria Decision Making, Tool Pin Diameter, TOPSIS.

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining method using a non-consumable tool to join two facing workpieces without melting the fabric of the workpiece. Heat is produced by friction between the workpiece and the rotating tool, which is being traversed along the joint weld line, resulting in a softened region close to the FSW tool [1] (Fig. 1(a)). This tool has a rounded profile ended with a complicated pin. This pin is connected to the rounded profile by the shoulder. During welding, the shoulder rubs with the surface on top while the pin's role is to penetrate the workpiece [2]. FSW process was developed and used for welding plates in 1991 [3-4]. However, the friction stir welding of pipes (FSWoP) process was first developed after a considerable amount of time specifically in 2002 [5].



(a) FSW of plates process (b) FSWoP process

Figure 1. A schematic drawing of the friction stir welding process for both plates and pipes.

FSWoP process needs a special design of complex fixture to hold the two parts of pipes being welded and allow a rotation motion for them – as the travel speed in plates – (Fig. 1 (b)). Also, the tool in FSWoP process has a slightly different design due to welding surface variation.

A lot of studies have been conducted to optimize the FSW process of plates and also the FSWoP process [6]. Generally, the significant parameters that affect the two processes are as follows: rotational speed of the tool [7, 8], travel speed which is dedicated to the tool in FSW process of plates [9] while it is referred to the rotational speed of pipes in FSWoP process [10], tool pin profile [11, 12], joint thickness [13]. It was obvious from all these studies that the optimum levels of these parameters are not the same for optimizing the FSW of plates and the FSWoP process under the same conditions. As an example, the FSW of plates has been studied [14] and the FSWoP [15] under the same range of rotational speed. The effect of the rotational speed on the tensile strength of the joint for the plate is completely different from that for the pipe.

Clearly, the same parameter level may lead to different results while optimizing the FSW process of plates and

FSWoP process. Therefore, FSWoP process is considered as a different process from the FSW of plates despite using the same principle [10].

There are a limited number of optimization studies for the FSWoP. So, the optimization studies of the FSW process of plates will also be reviewed.

For the FSW process of plates and the FSWoP, the joint quality is assessed by the mechanical properties of the joint. Taguchi method is one of the optimization methods used to get the maximum tensile strength of the joint produced by the FSW process [16]. The mechanical properties are affected directly by the heat input through the FSW process. Optimization by Taguchi method was applied for minimizing the heat affected zone (HAZ) distance to the joint line [17]. This was performed with computer simulations by a temperature-field finite element model. Taguchi method was also incorporated with other techniques such as the Grey Relational Analysis (GRA) [18] to optimize the FSW process.

Another technique used for optimizing the FSW process was the response surface methodology (RSM). It is used to the highest values of the joint's mechanical properties directly [19, 20]. This was done by optimizing the process parameters after performing the experimental work. RSM was applied as a grey-fuzzy based approach to optimize the FSW process in [21].

Multi criteria decision making techniques have also played a role in optimizing the FSW process of plates. FSW process parameter was optimized using the GRA in [22] for attaining higher mechanical properties of the joint. Taguchi based GRA was used as a technique for optimizing the FSW process as stated earlier. Other examples from the literature can be found in [23, 24]. TOPSIS also used for optimizing the FSW process of plates. It was used as a selection tool for alternative solutions generated by particle swarm optimization [25]. Both GRA and TOPSIS were used for optimizing the tool rotational speed, welding speed and tool offset of the FSW process of plates in [26].

Most of the studies in the literature review have been limited to optimizing the FSW process of plates. And to the best knowledge of the authors, MCDT techniques have not been applied to the FSWoP process yet. The contributions of this paper can be summarized as follows:

1. Using the MCDM techniques to optimize the FSWoP process.
2. The first paper to study the effect of the tool pin diameter on the FSWoP process.
3. Introducing a new designed fixture for the FSWoP process implemented on a vertical milling machine.

The structure of the paper is as follows: in Section 2, the design of experiments is outlined, and the description of the parameters considered are presented. Section 3 presents the methodology used through the experimental work. The MCDM techniques are outlined and discussed in Section 4. The results are presented and discussed in Section 5. Finally, Section 6 concludes the work and suggests several future research directions.

II. DESIGN OF EXPERIMENTS

Taguchi method is a popular technique for the design of experiments process, as it produces a smaller number of experiments to be carried out than the full factorial design. However, the full factorial design has been proved to be better in analysis by non-confounding the mutual effect of the parameters [27]. So, the penalty of not using Taguchi method was to have a larger number of experiments to perform and it was accepted to have a good analysis. The first step is to define the considered parameters of the FSWoP and their levels for the design of experiments process. The main parameter to be considered in this paper is the tool pin diameter. Also, based on trial experiments, literature review, the rotational speed and travel speed are selected with the main parameter. Three levels were assigned to each factor. The values of the parameters associated their levels are tabulated in Table 1. So, number of experiments = $3^3 = 27$ would be the basis for studying the effects of the three factors on the responses: the tensile strength and hardness of the welded joint.

Table 1 FSWoP process parameters and their levels.

Parameter	**Unit**	**Level**		
		-1	0	1
Pin Diameter (D)	mm	3	4	5
Rotation speed (N)	RPM	1000	1200	1800
Travel speed (S)	mm/min	10	20	30

III. METHODOLOGY

3.1. MATERIALS

The FSWoP process was conducted to join two pieces of Al 6061 pipes. Each pipe was 30 mm in outer diameter and 3 mm in thickness. Table 2 shows the chemical composition of the Al 6061 material of the pipes.

Table 2 Chemical composition (wt. %) of Al 6061

Wt. %	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**
	Bal	0.2	0.3	0.1	0.4	0.9	0.04	0.1	0.12

3.2. MACHINE

A vertical milling machine prepared and equipped for the FSWoP process was used as in [28]. The preparation of the machine usually involves a fixture design that can accommodate a rotating motion of the pipe – as a parameter, it is the travel speed (S) – to allow the advancing motion of the tool over the weld line (Fig. 1 (b)).

3.3. FIXTURE

The first fixture used in the FSWoP process [10] was composed of a solid rod back ended with a threaded part as shown in Fig. 2. The two pipes are assembled on the rod and tightened with a washer and a nut. This fixture was efficient and provided several good quality samples. However, the issue was always to get off the pipe from this fixture after welding. Internal axial hammer support was used to perform this hard task. That stimulates to design a new design fixture to eliminate this post welding hard task.

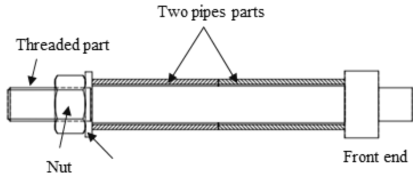


Figure 2 The old fixture design.

In the new design, the solid rod is decomposed into two parts connected with alike gear teeth (Fig. 3). After welding and loosing the nut, the rod two parts are disassembled, and every part is removed easily from inside the pipe.

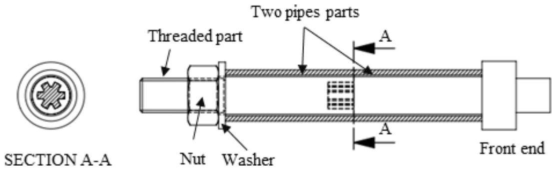


Figure 3 The new fixture design.

3.4. TOOL

Three unique non-consumable instruments made of hard tool steel with pin diameters (D) equal to 3, 4 and 5 mm used to weld aluminum pipes. The pin profile is tapered with initial diameter equal to D when the final diameter is 1 mm with length 3 mm. A shoulder with an elliptical 10 × 9 mm profile and a height of 5 mm connected the pin to the main tool body. The tool (rotated 90 degrees) that was used for the experimentation is shown in Fig. 4.

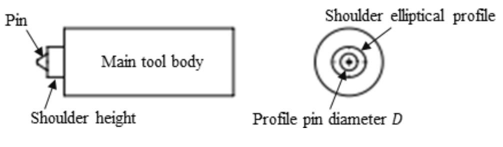


Figure 4 The new fixture design.

3.5. MEASUREMENTS AND TESTS

Generally, the efficiency of the welded joint is measured by its mechanical properties. The tensile strength was measured by the destructive tensile test whilst the Vickers hardness test was used to measure the hardness. Three tensile specimens were cut from the each welded joint and each specimen had a configuration as shown in Fig. 5.

Figure 5 The configuration of the tensile specimen cut from the pipes welded.

The tensile strength value (UTS) which was reported was the average value of these three specimens. Vickers hardness number (VHN) was measured at points distributed over the weld zone and the average was calculated for each specimen. Both values of UTS and VHN for each run is mentioned in Table (4).

IV. MCDM TECHNIQUES

4.1. GRAY RELATIONAL ANALYSIS (GRA)

GRA is a method of multi-objective optimization that turns multi-response into a single objective issue. GRA was created to evaluate the uncertainties of structures, system interactions, etc. [29]. In GRA, all yield values are normalized between zero and one. These normalized values are used to calculate each output response's gray relational coefficient. The gray relational grade (GRG) is then calculated for each experimental run by averaging the gray relational coefficient. The greater GRG gives ideal solution characteristics. The following steps will be taken in the GRA:

First, Eq. (1) is used to normalize the output responses for "larger the better" condition.

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{1}$$

Where $x_i(k)$ is the normalized value of output response, $\min y_i(k)$ is least value of $y_i(k)$ for kth response, $max\, y_i(k)$ is highest value of $y_i(k)$ for kth response.

Second, grey relational coefficient ($\zeta_i(k)$) is needed to be generated by Eq. (2) to make a relation between the actual normalize value and the ideal one.

$$\zeta_i(k) = \frac{\Delta_{min} + \psi\Delta_{max}}{\Delta_{oi}(k) + \psi\Delta_{max}} \tag{2}$$

$\Delta_{oi}(k)$ is a set of calculated values where $\Delta_{oi}(k) = |x_0(k) - x_i(k)|$. The minimum and maximum values of the set are taken as Δ_{min}, Δ_{max} respectively. ψ is distinctive coefficient, whose rule is to determine the grey relational coefficient's range. It is usually in the range [0- 1]. But it doesn't affect the rank of the coefficient. The suggested value of ψ is "0.5" [30].

Third, by Eq. (3), the GRG (γ_i) is calculated based on the number of output responses (n).

$$\gamma_i = \frac{1}{n}\sum_{i=1}^{n}\zeta_i(k) \qquad (3)$$

4.2. SIMILAR TO THE IDEAL SOLUTION, TECHNIQUES FOR ORDER PREFERENCES (TOPSIS)

TOPSIS is a MCDM technique that provides a way to get the optimum solution from many alternative ones. This optimum solution is the closet to the ideal positive solution and the furthest from the ideal negative one. TOPSIS technique can be outlined in the following steps:

First, the decision matrix (D_m) is constructed using the experimental results acquired by Eq. (4). In the decision matrix, each response is considered as a characteristic and there are n characteristicsw while the experiments are considered to be options with a total number of $m$options.

$$D_m = \begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & \cdots & a_{mn} \end{bmatrix} \qquad (4)$$

Where a_{ij} is the measure of jth characteristic to ith alternative.

Second, as in GRA, the decision matrix can be normalized using Eq. (5).

$$\gamma_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \qquad (5)$$

Where γ_{ij} is normalized value for $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$.

The third step is achieved by assigning the weight of each characteristic where the sum of all weights for one characteristic is equal to 1. Eq. (6) is used to calculate the weight normalized decision matrix.

$$\varphi_{ij} = w_j \gamma_{ij} \qquad where\ \sum_{j=1}^{n} w_j = 1 \qquad (6)$$

Table 4 Experimental results for each run

Run	*D*	*N*	*S*	*UTS (MPa)*	*VHN*
1	3	1000	10	205.57	65
2	4	1000	10	232.09	67
3	5	1000	10	170.2	66
4	3	1000	20	211.68	66.2
5	4	1000	20	239.81	70
6	5	1000	20	225.65	68
7	3	1000	30	203.53	64.1
8	4	1000	30	208.71	62.7
9	5	1000	30	196.37	60.8
10	3	1400	10	238.59	64
11	4	1400	10	261.61	62.4
12	5	1400	10	149.69	61.9
13	3	1400	20	161.24	60.3
14	4	1400	20	239.01	69
15	5	1400	20	167.18	58.3
16	3	1400	30	206.7	65
17	4	1400	30	228.34	55.1
18	5	1400	30	163.55	54.3
19	3	1800	10	210.21	52
20	4	1800	10	164.98	49
21	5	1800	10	158.76	46.3
22	3	1800	20	227.5	62
23	4	1800	20	176.14	46
24	5	1800	20	272.05	65
25	3	1800	30	209.53	69.6
26	4	1800	30	151.69	41
27	5	1800	30	208.23	68.4

After that, Eq. (7) and (8) are used to get the positive ideal solution (PIS) and negative ideal solution (NIS):

$$\begin{aligned}\varphi^+ &= (\varphi^+, \varphi^+, \ldots, \varphi^+) \\ &= \{(\max \varphi_{ij} \mid j \in J_1), (\min \varphi_{ij} \mid j \in J_2)\}\end{aligned} \qquad (7)$$

$$\begin{aligned}\varphi^- &= (\varphi^-_1, \varphi^-_2, \ldots, \varphi^-_n) \\ &= \{(\min \varphi_{ij} \mid j \in J_1), (\max \varphi_{ij} \mid j \in J_2)\}\end{aligned} \qquad (8)$$

Where J_1 is set of useful characteristics and J_2 is a set of non-useful characteristics.

Then, how far or close each alternative from the PIS and NIS need to be measured? This can be determined by Eq. (9) and Eq. (10), where $S^+$and S^-_i is the separation distance for alternative i from PIS and NIS respectively.

$$S_i^+ = \sqrt{\sum_{i=1}^{n} (\varphi_{ij} - \varphi^+)^2} \qquad (9)$$

$$S_i^- = \sqrt{\sum_{i=1}^{n} (\varphi_{ij} - \varphi^-)^2} \qquad (10)$$

Finally, each separation distance is transformed into a weighted relative coefficient, the relative closeness coefficient (CC), using Eq. (11).

$$CC = \frac{S_i^-}{S_i^+ - S_i^-} \qquad (11)$$

V. RESULTS AND DISCUSSION

5.1. EFFECT OF PROCESS PARAMETERS

The main effects on the UTS and hardness of the welded joints are plotted in Fig. 7(a) and (b). It is obvious in Fig. 7(a) that all the three parameters have significant effects on the UTS of the welds. The welded joint's UTS increases with the increase in the tool pin diameter until a certain value, the behavior is reversed. So, an optimum value of the tool pin diameter should be determined to produce a good weld joint between the pipes. The frictional heat generated due to the stirring action of the tool pin are the main dominator of the heat input and temperature distribution in the joint. On the opposite, the UTS was increased directly with the travel speed after the value of 20 mm/min. While the effect of the tool rotational speed is nonbeneficial to the UTS of the joint. The UTS is decreased with the increase of the rotational speed.

From Fig. 7 (b), it is noted that the tool pin diameter almost has no effect on the hardness of the weld joint, whereas the hardness decreased with the increase in the rotational speed generally and steeply after 1400 RPM. The decrease of the hardness is because of the coarse grain structure formed by the heat generation resulted from the higher tool rotational speed [31, 32]. The effect of the travel speed on the joint's hardness was almost the same on the UTS of the weld joint.

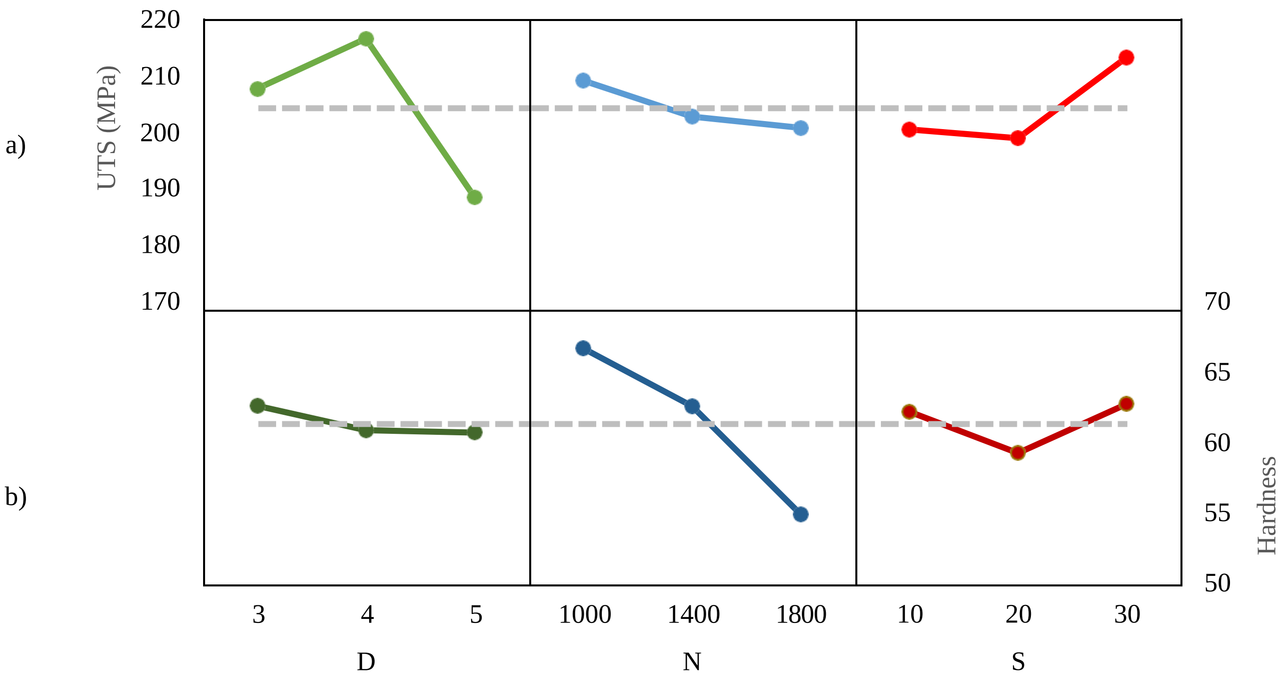


Figure 6 Main effects plot data means for (a) UTS and (b) hardness

Figure 8(a) and (b) represents the interaction effects of the FSWoP process parameters on the weld joint's UTS and hardness. From Figure 8(a), it can be concluded that at lower values of the tool pin diameter, the tool rotational speed had a more marked effect on the UTS, whereas at higher values of the tool pin diameter range, both the tool rotational speed and the travel speed had pronounced effects on UTS. Also, at higher values of the travel speed, the tool rotational speed has a significant influence on UTS, but the opposite was not true. Therefore, it can be concluded that all the three parameters have significant effects on UTS. It can't be said that one parameter had a greater or lesser effect on UTS than others.

On the other hand, from Fig. 8(b) it can be inferred that that tool rotational speed had a pronounced effect on the joint's hardness than the others.

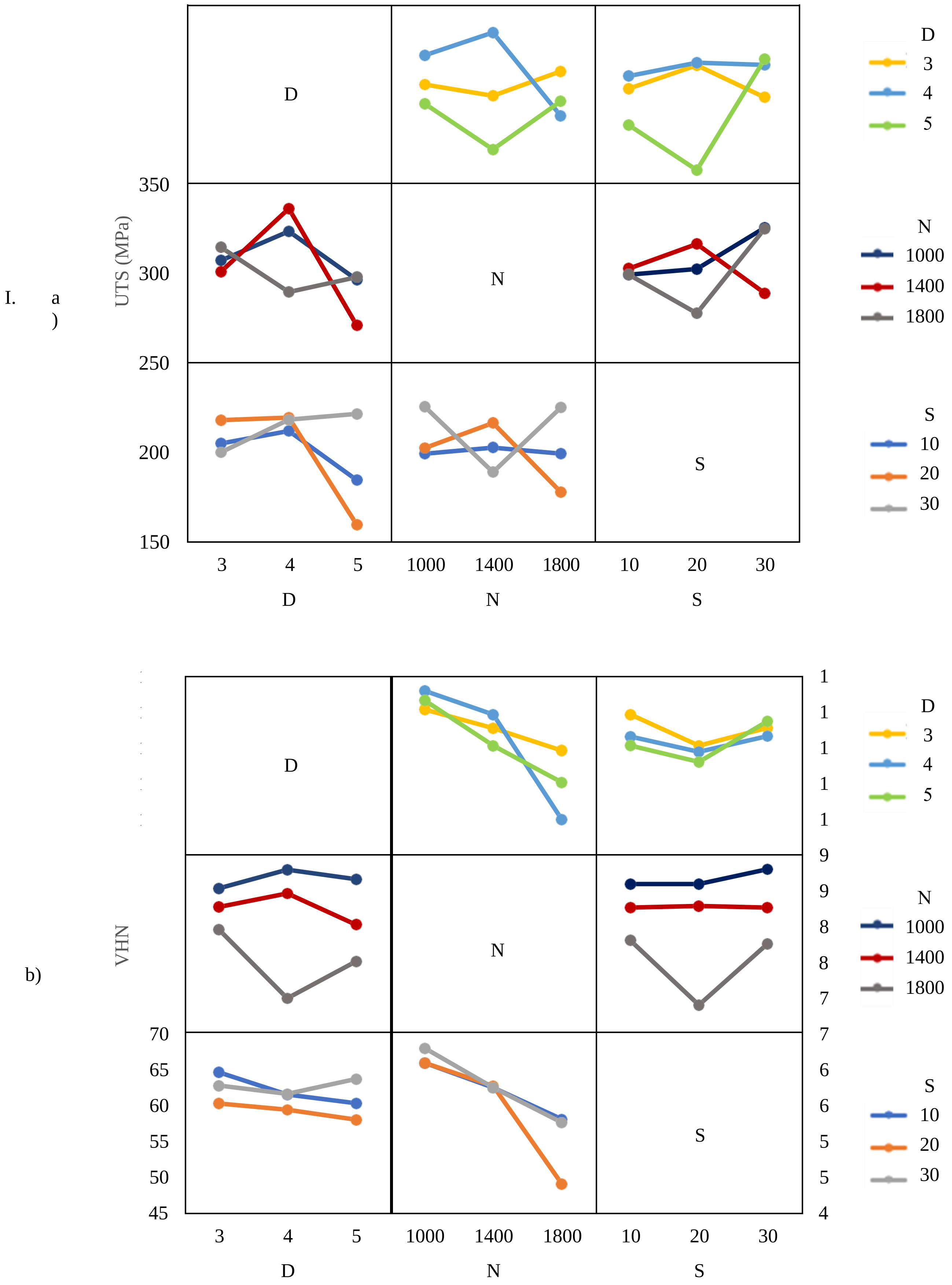


Figure 7 Interaction plot data means for (a) UTS and (b) VHN.

6.1. GRA

As the aim of the optimization process is to maximize the considered responses: the UTS and hardness of the welded joint, the output responses were normalized for larger the better using Eq. (1). Using the procedure mentioned in Section 4.1., the normalized values for all runs of the experimental work, the gray coefficient and the GRG were calculated and recorded in Table (5).

The optimal solution is the one with the highest GRG, in other orders the closet to value of 1. The run no. 24 of the experiments performed has the largest GRG of value = 0.6829. So, this run provides better output responses: UTS and hardens of the welded joint. The tool pin diameter, the rotational speed and the travel speed of values 5 mm, 1800 RPM and 20 mm/min respectively lead to the best results among the experimented runs.

To determine the optimum values of parameters that leads to maximum responses, a mean gray relational grade (MGRG) should be calculated at all levels of the parameters. Table (6) illustrates the MGRG at each level of every parameter. The optimal level for each parameter is the one whose MGRG is the highest. From Table 6, the optimum parameters are 4 mm, 1800 rpm and 10 mm/min for the tool pin diameter, rotational speed and travel speed respectively. The effect of process parameter on GRG is illustrated in Fig. 8(a). Fig. 8(a) reveals that for acquiring higher UTS and hardness of the welded joint, the rotational speed should be at the highest level while the travel speed at the lowest with a pint tool diameter of 5 mm.

6.2. TOPSIS

Forming the decision matrix, that consists of experimental runs and output responses represented as alternatives and attributes, is the first step performed using Eq. (5). Equal weight is given to each output response that means 1/2 relative weight for UTS and hardness of the welded joint.

Completing the procedure as in Section 4.2, all calculated values are tabulated in Table 7.

The CC in TOPSIS is equivalent to the GRG in GRA. So, the alternative with the largest CC is considered to be the best solution. The run no. 24 of CC = 0.0457 is the optimum solution. The mean closeness coefficient (MCC) of every parameter at each level is found and mentioned in Table 8. Also, the effect of each level of parameter on the MCC value is shown in Figure 8(b). The same conclusion can be deduced from Fig. 8(b) as in Fig 8(a) about the levels for getting higher UTS and hardness of the welded joint.

Table 5 GRA analysis results

Run	**Normalized**		**Grey coefficient**		**GRG**
	UTS	**Hardness**	**UTS**	**Hardness**	
1	0.457	0.867	0.479	0.790	0.634
2	0.673	0.067	0.605	0.349	0.477
3	0.168	0.100	0.375	0.357	0.366
4	0.507	0.093	0.503	0.356	0.429
5	0.737	-0.033	0.655	0.326	0.491
6	0.621	0.033	0.569	0.341	0.455
7	0.440	0.163	0.472	0.374	0.423
8	0.482	0.210	0.491	0.388	0.440
9	0.382	0.273	0.447	0.408	0.427
10	0.727	0.167	0.647	0.375	0.511
11	0.915	0.220	0.854	0.391	0.622
12	0.000	0.237	0.333	0.396	0.365
13	0.094	0.290	0.356	0.413	0.385
14	0.270	0.000	0.407	0.333	0.370
15	0.143	0.357	0.368	0.437	0.403
16	0.466	0.133	0.484	0.366	0.425
17	0.643	0.463	0.583	0.482	0.533
18	0.113	0.490	0.361	0.495	0.428
19	0.495	0.567	0.497	0.536	0.517
20	0.125	0.667	0.364	0.600	0.482
21	0.074	0.757	0.351	0.673	0.512
22	0.074	0.233	0.351	0.395	0.373
23	0.216	0.767	0.390	0.682	0.536
24	1.000	0.133	1.000	0.366	0.683
25	0.489	-0.020	0.495	0.329	0.412
26	0.016	0.933	0.337	0.882	0.610
27	0.478	0.020	0.489	0.338	0.414

Table 6 MGRG of each parameter

Level	***D***	***N***	***S***
-1	0.4563	0.4602	**0.4983**
0	**0.5066**	0.4489	0.4581
1	0.4502	**0.5040**	0.4567

The optimum results acquired by GRA and TOPSIS give the same values of process parameters as an optimum one. It reveals that both techniques GRA and TOPSIS gave the same optimal solution of the process parameters set for getting better output responses: UTS and hardens of the welded joint.

Table 7 TOPSIS analysis results

Run	Normalized		Grey coefficient		GRG
	UTS	Hardness	UTS	Hardness	
1	0.192	0.204	0.021	0.031	0.031
2	0.217	0.211	0.013	0.037	0.037
3	0.159	0.208	0.032	0.027	0.027
4	0.198	0.208	0.019	0.033	0.033
5	0.224	0.22	0.01	0.041	0.041
6	0.211	0.214	0.015	0.037	0.037
7	0.19	0.202	0.022	0.029	0.029
8	0.195	0.197	0.021	0.029	0.029
9	0.183	0.191	0.026	0.025	0.025
10	0.223	0.201	0.012	0.037	0.037
11	0.244	0.196	0.009	0.041	0.041
12	0.14	0.195	0.039	0.022	0.022
13	0.151	0.19	0.036	0.021	0.021
14	0.223	0.217	0.01	0.04	0.04
15	0.156	0.183	0.035	0.019	0.019
16	0.193	0.204	0.021	0.031	0.031
17	0.213	0.173	0.073	0.029	0.029
18	0.153	0.171	0.038	0.015	0.015
19	0.196	0.164	0.027	0.022	0.022
20	0.154	0.154	0.04	0.01	0.01
21	0.148	0.146	0.043	0.006	0.006
22	0.213	0.195	0.016	0.033	0.033
23	0.165	0.145	0.039	0.01	0.01
24	0.254	0.204	0.005	0.046	0.046
25	0.196	0.219	0.02	0.035	0.035
26	0.142	0.129	0.048	0.001	0.001
27	0.195	0.215	0.02	0.034	0.034

Table 8 MCC of each parameter

Level	*D*	*N*	*S*
-1	0.026	0.028	**0.030**
0	**0.031**	0.022	0.027
1	0.025	**0.0322**	0.0256

VII. CONCLUSION

By analysis of the experimental work of the FSWoP process, it is obvious that the tool pin diameter has a significant effect on the mechanical properties of the welded joint: UTS and hardness. These two properties were considered as output responses of an optimization process. That stimulated the using of MCDM techniques to optimize the parameters to maximize the output responses. GRA and TOPSIS were efficiently applied for optimizing the FSWoP process.

The present work considered tensile strength, and hardness for analysis. The research demonstrates that similar to GRA, TOPSIS is also an effective instrument for optimizing the issue of various requirements in friction stir welding, since both techniques have the same process parameter mix as the optimum value.

The peak tool rotational speed value, minimum welding speed value and pin diameters at 5 mm produce maximum tensile strength, and hardness, according to TOPSIS. Rotational speed 1800 RPM, welding speed 10 mm / min and pin diameter 5 mm are the optimum process parameter conditions of the gray relationship assessment.

The experimental results show that the performance characteristics of the Friction stir welding process using rotation speed and travel speed with pin diameter base are improved together by employing the proposed approach.

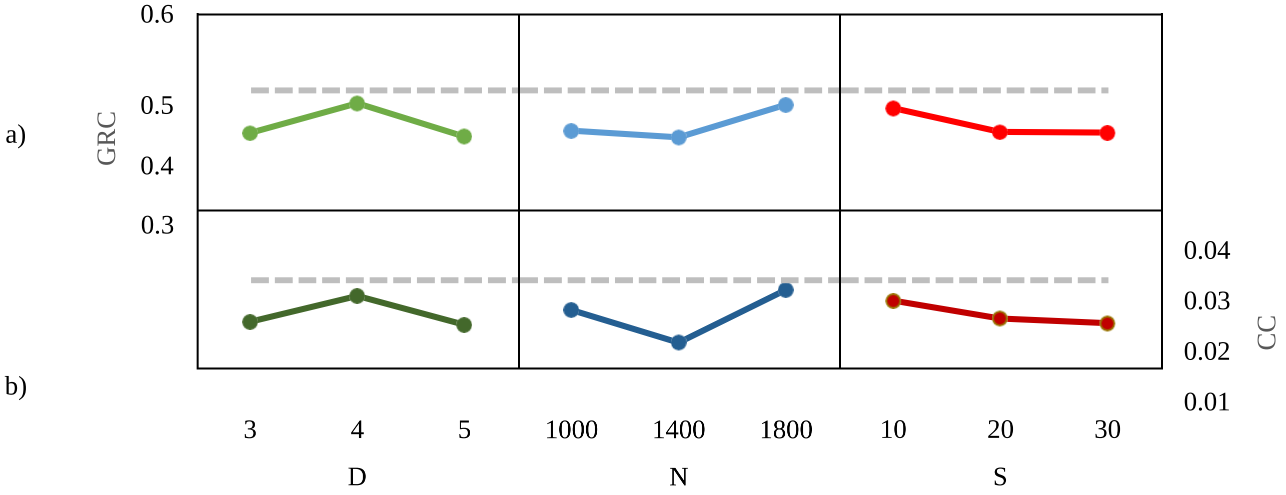


Figure 8 Effect of process parameter on closeness coefficient by (TOPSIS)

REFERENCES

[1] Thomas, W. M., and C. J. Dawes. "Friction stir process welds aluminum alloys," *Weld. Journal,* 75:41-45, 1996.

[2] Mishra, Rajiv S., and Z. Y. Ma. "Friction stir welding and processing," *Materials science and engineering: R: reports*, 50(1-2):1-78, 2005.

[3] Dawes, C. J., and Thomas, W., M., "Friction Stir Process Welds Aluminum Alloys," Welding Journal, 75(3):41–45, 1996.

[4] Dawes, C. J., "Introduction to Friction Stir Welding and Its Development," Welding and Metal Fabrication, 63(1):13–15, 1996.

[5] Engelhard, G., and Hillers, T., "Orbital friction stir welding of aluminium pipes," In *Welding in plant and tank construction. Proceedings*, 2002.

[6] Gite, R. A., Loharkar, P. K. and Shimpi, R., "Friction stir welding parameters and application: A review," *Materials Today*: Proceedings, 2019.

[7] Prabha, K. A., Putha, P. K., and Prasad, B. S., "Effect of Tool Rotational Speed on Mechanical Properties of Aluminium Alloy 5083 Weldments in Friction Stir Welding," *Materials Today*: Proceedings, 5(9):18535–18543, 2018.

[8] Hattingh, D. G., Von Welligh, L. G., Bernard, D., Susmel, L., Tovo, R., and James, M. N., "Friction Stir Welding of 38 mm OD 6082-T6 Aluminium Tubes," *Journal of Materials Processing Technology*, 238:255–266, 2016.

[9] Prabhu, S., Shettigar, A. K., Rao, K., Rao, S., and Herbert, M., "Influence of welding process parameters on microstructure and mechanical properties of friction stir welded aluminium matrix composite," In *Materials Science Forum*, 880:50–53, 2017.

[10] Khourshid, A. M., and Sabry, I., "Analysis and design of Friction stir welding," *International Journal of Mechanical Engineering & Robotics Research,* 2(3):233-241, 2013.

[11] Moosabeiki, V., Azimi, G., and Ghayoor, M., "Influences of Tool Pin Profile and Tool Shoulder Curvature on The Formation of Friction Stir Welding Zone in AA6061 Aluminium Alloy," *Advanced Materials Research*, 445:789–794, Trans Tech Publications, 2012.

[12] Sabry, I., and El-Kassas A. M., "Comparative Study on Different Tool Geometrics in Friction Stirred Aluminum Welds Using Response Surface Methodology," 4th International Conference on Welding and Failure Analysis of Engineering Materials (WAFA), 2018.

[13] Khourshid, A. M., El-Kassas, A. M., Hindawy, H. M., and Sabry, I., "Optimization of Friction Stir Welding Parameters for Joining Aluminum Pipes Using Regression Analysis," *International Journal of Civil. Mechanical and Energy Science (IJCMES),* 2(1), 1-5, 2016.

[14] AL-Murshdy, J. and Chabuk, Q., "Effect of Tool Shape Geometry and Rotation Speed in Friction Stir Welding of 2024-T3," *The Iraqi Journal for Mechanical and Material Engineering*, 16(3):176-185, 2016

[15] Khourshid, A. M., El-Kassas, A. M., and Sabry, I., "Integration between artificial neural network and responses surfaces methodology for modeling of friction stir welding," *International Journal of Advanced Engineering Research and Science*, 2(3):67–73, 2015.

[16] Koilraj, M., Sundareswaran, V., Vijayan, S., & Rao, S. K., "Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083–Optimization of process parameters using Taguchi technique," *Materials & Design*, 42, 1-7, 2012.

[17] Nourani, M., Milani, A. S., and Yannacopoulos, S., "Taguchi optimization of process parameters in friction stir welding of 6061 aluminum alloy: A review and case study," *Engineering*, *3*:144-155, 2011.

[18] Sahu, P. K., and Pal, S., "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, 2015.

[19] Al-Jarrah, J. A., "Optimization of friction stir welding parameters for joining aluminum alloys using RSM," *Doctoral dissertation, Al-Balqa Applied University, Jordan*, 2013.

[20] Elatharasan, G., & Kumar, V. S., "An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM," *Procedia Engineering*, *64*:1227-1234, 2013.

[21] Vijayan, D., and Rao, V. S., "Optimization of friction stir welding process parameters using RSM based Grey–Fuzzy approach," *Saudi Journal of Engineering and Technology, 2*(1):12-25, 2017.

[22] Kasman, Ş., "Optimisation of dissimilar friction stir welding parameters with grey relational analysis," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(9):1317-1324, 2013.

[23] Vijayan, S., Raju, R., and Rao, S. K., "Multiobjective optimization of friction stir welding process parameters on aluminum alloy AA 5083 using Taguchi-based grey relation analysis," *Materials and Manufacturing Processes, 25*(11):1206-1212, 2010.

[24] Kasman, Ş., "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, 2013,

[25] Shojaeefard, M. H., Behnagh, R. A., Akbari, M., Givi, M. K. B., and Farhani, F., "Modelling and Pareto optimization of mechanical properties of friction stir welded AA7075/AA5083 butt joints using neural network and particle swarm algorithm," *Materials & Design*, *44*:190-198, 2013.

[26] Sudhagar, S., Sakthivel, M., Mathew, P. J., and Daniel, S. A. A., "A multi criteria decision making approach for process improvement in friction stir welding of aluminium alloy," *Measurement*, 108:1-8, 2017.

[27] Rafidah, A., Nurulhuda, A., Azrina, A., Suhaila, Y., Anwar, I. S., and Syafiq, R. A., "Comparison Design of Experiment (DOE): Taguchi Method and Full Factorial Design in Surface Roughness," *Applied Mechanics and Materials*, 660:275–279, Trans Tech Publications, 2014.28

[29] Kuo, Y., Yang, T., and Huang, G. W., "The use of grey relational analysis in solving multiple attribute decision-making problems," *Computers & Industrial Engineering*, 55(1):80-93, 2008.

[30] Kuo, Y., Yang, T., and Huang, G. W., "The use of a grey-based Taguchi method for optimizing multi-response simulation problems," *Engineering Optimization*, 40(6):517-528, 2008.

[31] Babu, S., Elangovan, K., Balasubramanian, V., and Balasubramanian, M., "Optimizing friction stir welding

parameters to maximize tensile strength of AA2219 aluminum alloy joints," *Metals and Materials International*, 15(2):321-330, 2009.

[32] Ahmadkhaniha, D., Sohi, M. H., Zarei-Hanzaki, A., Bayazid, S. M., and Saba, M., "Taguchi optimization of process parameters in friction stir processing of pure Mg," *Journal of Magnesium and Alloys*, 3(2):168-172, 2015.