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# Multi-response Optimization of Friction Stir Welding Process Parameters Using Standard Deviation (SD) Based Preference Indexed Value (PIV) Method

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***Abstract :*** *In this paper, standard deviation (SD) based preference indexed value (PIV) multi-criteria decision making (MCDM) method has been applied to solve multiresponse optimization problem of friction stir welding (FSW) process. The MCDM problem considered in the present work pertains to the selection of optimum FSW process parameters. The results obtained using the SD based PIV method almost agree with those derived by the past researchers which prove the applicability, efficacy, potentiality, and flexibility of this simple novel method for solving complex multiresponse optimization problem.*

***Keywords:*** *Multi-response optimization, MCDM, Friction stir welding, Standard deviation, PIV method.*

## 1. INTRODUCTION

Friction stir welding (FSW) is a solidstate welding process which was invented and patented in1991. In this process the joint is obtained by plunging a rotating tool into abutting surfaces of the base material (BM) and traversing in the welding direction to complete the weld [1]. In FSW, welding takes place by frictional heat and plastic deformation of the base material. The schematic of the FSW process is shown in Fig. 1. The FSW joint quality depends upon proper selection of the FSW process parameters such as rotational speed, traverse speed, tool shoulder diameter, tool pin profile, tilt angle, plunge depth etc. and therefore, it is necessary to select optimal parameters to obtain good quality joints. Studies have reported the effect of the various FSW process parameters on joint quality [1, 2]. Selection of the suitable FSW parameters is indeed, a multi-criteria decision making problem as it involves several conflicting criteria and hence, MCDM methods can be used to determine the optimal process parameters that will lead to the attainment of the laid down objectives. In the past researchers have used several MCDM methods and other mathematical techniques to solve different MCDM problems such as AHP [3], TOPSIS [4-5], VIKOR [6], comprehensive VIKOR methods [7-8], MOORA method [9], grey relational analysis method [10-11], graph theory and matrix approach [12], PROMETHEE method [13], different preference ranking-based methods [14-15], ELECTRE method [16-18] and many more.

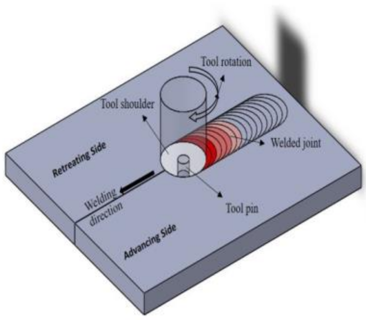


Fig. 1 Schematic of Friction stir welding process

Some of these methods/techniques involve quite complex computational procedure. Recently, a novel MCDM method, based on the Proximity Indexed Value (PIV), has been developed by Mufazzal and Muzakkir [19] for which it has been proved that it minimizes the alternatives' rank reversal problem leading to the attainment of more robust and reliable results of the decision-making problems. Moreover, this method involves only seven simple computational steps in ranking the alternatives, and the steps are independent of the length of decision matrix. For solving an MCDM problem, criteria weights need to be calculated and for this purpose several methods such as analytic hierarchy process, standard deviation, entropy, principal component analysis etc. are available. However, standard deviation (SD) method appears to be the simplest one for criteria weights determination. Keeping in view the simplicity of the SD method and merits of PIV method, an attempt has been made in this paper to explore the efficacy, utility, potentiality, and flexibility of the SD based PIV MCDM method for solving multi-response optimization problem of FSW which has already been solved by the past researcher using multi-objective optimization on the basis of ratio analysis (MOORA) method. The remainder of this paper is organized as follows: Section 2 presents the steps of the SD method used to determine criteria weights. Section 3 briefs the steps of on the Proximity Indexed Value (PIV) based method. Section 4 illustrates application of the proposed SD based PIV method for determination of the optimal FSW process parameters and also compares the results with those of MOORA method. Section 5 presents conclusion of the present research.

## 2. STANDARD DEVIATION METHOD FOR CALCULATION OF CRITERIA WEIGHTS

The various steps of the standard deviation method are given below:

**Step 1**: Standardize the range of the response variables/criteria using Eq. (1)
where*max*, *min*are the maximum and minimum values of the criterion (*j*) respectively.

**Step 2**: Calculate the standard deviation (*SD*) for each response variable/criterion using Eq. (2).
where is the mean of the values of the$j^{th}$ criterion after normalization and $j = 1, 2, \ldots, n$ .

**Step 3**: Determine the weights, of all the response variables/criteria considered using Eq. (3).

## 3. PROXIMITY INDEXED VALUE (PIV) METHOD

This method involves the following simple steps:

**Step 1** : Identify the available alternatives *Ai* (*i* = 1, 2,...., *m*) and decision criteria *Cj* (*j* = 1, 2, ...., *n*) involved in the decisionproblem.

**Step 2**: Formulate the decision matrix *Y* by arranging alternatives in rows and criteria in columns as given in Eq.(4)
where, *Yij* represents *i*th alternative performance value on *j*th criterion, *m* is the number of alternatives, and *n* is the number of criteria.

**Step 3**: Determine the normalized decision matrixusing Eq. (5)

**Step 4**: Determine the weighted normalized decision matrix using Eq. (6)
where, *wj* is the weight of the *j*th criterion.

**Step 5**: Evaluate the Weighted Proximity Index (WPI), using Eq. (7)

**Step 6**: Determine the Overall Proximity Value, using Eq. (8)

**Step 7** : Rank the alternatives based on values. The alternative with least value of *di* represents minimum deviation from the best and therefore, it is ranked first, followed by alternatives with increasing.

## 4. ILLUSTRATIVE EXAMPLE

This section presents an example pertaining to the selection of the FSW process parameters to optimize multi responses simultaneously using SD based PIV method to demonstrate applicability and efficacy of this method in providing solution to the multi-response optimization problem.

*Example: Friction Stir Welding Process*

This example is taken from Dinaharan and Murugan [20] in which the authors performed 31 trial runs of FSW by varying four process parameters i.e. rotational speed, welding speed, axial force and weight percentage of ZrB2and developed a mathematical model to predict ultimate tensile strength (UTS) and joint efficiency (η). They optimized the FSW process parameters using generalized reduced gradient method (GRG) to maximize both UTS and η. Gadakh et al. [21] also solved this problem using multi-objective optimization on the basis of ratio analysis (MOORA) method.Table 1 shows the 31 trial runs and the two attributes i.e. UTS and η. Both these attributes are the beneficial criteria whose high values are required.

Table 1. Decision Matrix[20]

| Trial Run | Rotational Speed(rpm) | Welding Speed (mm/min) | Axial Force (kN) | $ZrB_2$ (wt %) | UTS (MPa) | η (%) |
|---|---|---|---|---|---|---|
| T01 | 1075 | 40 | 5 | 2.5 | 154.25 | 75.99 |
| T02 | 1225 | 40 | 5 | 2.5 | 162.65 | 80.12 |
| T03 | 1075 | 60 | 5 | 2.5 | 133.23 | 68.09 |
| T04 | 1225 | 60 | 5 | 2.5 | 153.06 | 75.40 |
| T05 | 1075 | 40 | 7 | 2.5 | 153.46 | 74.12 |
| T06 | 1225 | 40 | 7 | 2.5 | 145.61 | 71.73 |
| T07 | 1075 | 60 | 7 | 2.5 | 144.5 | 71.18 |
| T08 | 1225 | 60 | 7 | 2.5 | 145.78 | 71.81 |
| T09 | 1075 | 40 | 5 | 7.5 | 179.29 | 74.70 |
| T10 | 1225 | 40 | 5 | 7.5 | 180.36 | 75.15 |
| T11 | 1075 | 60 | 5 | 7.5 | 161.78 | 67.41 |
| T12 | 1225 | 60 | 5 | 7.5 | 157.92 | 65.80 |
| T13 | 1075 | 40 | 7 | 7.5 | 177.17 | 73.82 |
| T14 | 1225 | 40 | 7 | 7.5 | 166.28 | 69.28 |
| T15 | 1075 | 60 | 7 | 7.5 | 155.67 | 64.86 |
| T16 | 1225 | 60 | 7 | 7.5 | 173.83 | 72.43 |
| T17 | 1000 | 50 | 6 | 5 | 129.12 | 58.43 |
| T18 | 1300 | 50 | 6 | 5 | 143.25 | 64.82 |
| T19 | 1150 | 30 | 6 | 5 | 140.56 | 63.60 |
| T20 | 1150 | 70 | 6 | 5 | 133.65 | 60.48 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T21 | 1150 | 50 | 4 | 5 | 135.44 | 61.29 |
| T22 | 1150 | 50 | 8 | 5 | 145.12 | 65.67 |
| T23 | 1150 | 50 | 6 | 0 | 190.33 | 99.13 |
| T24 | 1150 | 50 | 6 | 10 | 241.67 | 95.52 |
| T25 | 1150 | 50 | 6 | 5 | 199.23 | 90.15 |
| T26 | 1150 | 50 | 6 | 5 | 211.28 | 95.60 |
| T27 | 1150 | 50 | 6 | 5 | 200.19 | 90.58 |
| T28 | 1150 | 50 | 6 | 5 | 209.83 | 94.95 |
| T29 | 1150 | 50 | 6 | 5 | 196.12 | 88.74 |
| T30 | 1150 | 50 | 6 | 5 | 206.34 | 93.37 |
| T31 | 1150 | 50 | 6 | 5 | 198.65 | 89.89 |

Weights of the two criteria i.e. UTS and η were calculated using Eq. (1) to Eq. (3) and they were found as $W_{UTS}$ = 0.4956 and $W\eta$ = 0.5404 respectively. The Weighted Normalized Values, Weighted Proximity Index (*ui*) and the Overall Proximity Value (*di*) for each trial run, as shown in Table 2, were calculated using Eq. (5) and Eq. (8),respectively, and the ranking of the alternatives was done based on the values of *di* . Table 2 also compares the rank of the trial runs obtained by the SD based PIV method with those derived by the MOORA method.

Table 2. Weighted proximity index, overall proximity index and ranking results

| | Weighte | | Weighte | | Ove | | Ran |
|---|---|---|---|---|---|---|---|
| T | | d | d | | rall | R | k |
| ri | Normali | | Proximit | | Prox | an | MO |
| al | zed | | y Index | | imit | k | OR |
| ru | Values | | (*ui*) | | y | | A |
| n | U | η | U | η | Val | | met |
| | TS | | TS | | ue | | hod |
| | | | | | (*di*) | | [21] |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 74 | 95 | 42 | 29 | 0.07 | | |
| 1 | 5 | 6 | 2 | 1 | 13 | 15 | 15 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 0 | 78 | 00 | 38 | 23 | 0.06 | | |
| 2 | 5 | 8 | 2 | 9 | 21 | 12 | 13 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 66 | 85 | 49 | 39 | 0.08 | | |
| 3 | 7 | 6 | 9 | 0 | 90 | 26 | 26 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 73 | 94 | 42 | 29 | 0.07 | | |
| 4 | 9 | 8 | 8 | 8 | 26 | 16 | 16 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 72 | 93 | 44 | 31 | 0.07 | | |
| 5 | 7 | 2 | 0 | 5 | 55 | 18 | 18 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 70 | 90 | 46 | 34 | 0.08 | | |
| 6 | 3 | 2 | 4 | 5 | 08 | 21 | 21 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 69 | 89 | 46 | 35 | 0.08 | | |
| 7 | 8 | 5 | 9 | 1 | 21 | 22 | 23 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 70 | 90 | 46 | 34 | 0.08 | | |
| 8 | 4 | 3 | 3 | 4 | 07 | 20 | 20 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 0 | 86 | 93 | 30 | 30 | 0.06 | | |
| 9 | 6 | 9 | 1 | 7 | 08 | 11 | 11 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 87 | 94 | 29 | 30 | 0.05 | | |
| 0 | 1 | 5 | 6 | 2 | 98 | 10 | 10 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | 0.07 | 19 | 19 |
| 1 | 78 | 84 | 38 | 39 | | | |
| 1 | 1 | 8 | 6 | 9 | 85 | | |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 76 | 82 | 40 | 41 | 0.08 | | |
| 2 | 3 | 7 | 4 | 9 | 24 | 23 | 22 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 85 | 92 | 31 | 31 | 0.06 | | |
| 3 | 6 | 8 | 1 | 8 | 30 | 13 | 12 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 80 | 87 | 36 | 37 | 0.07 | | |
| 4 | 3 | 1 | 4 | 5 | 39 | 17 | 17 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 75 | 81 | 41 | 43 | 0.08 | | |
| 5 | 2 | 6 | 5 | 1 | 46 | 24 | 24 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 83 | 91 | 32 | 33 | 0.06 | | |
| 6 | 9 | 1 | 8 | 6 | 63 | 14 | 14 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 62 | 73 | 54 | 51 | 0.10 | | |
| 7 | 3 | 5 | 3 | 2 | 55 | 31 | 31 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 69 | 81 | 47 | 43 | 0.09 | | |
| 8 | 2 | 5 | 5 | 1 | 07 | 27 | 27 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 1 | 67 | 80 | 48 | 44 | 0.09 | | |
| 9 | 9 | 0 | 8 | 7 | 35 | 28 | 28 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 2 | 64 | 76 | 52 | 48 | 0.10 | | |
| 0 | 5 | 1 | 2 | 6 | 08 | 30 | 30 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 2 | 65 | 77 | 51 | 47 | 0.09 | | |
| 1 | 4 | 1 | 3 | 6 | 89 | 29 | 29 |
| T | 0.0 | 0.0 | 0.0 | 0.0 | | | |
| 2 | 70 | 82 | 46 | 42 | 0.08 | | |
| 2 | 1 | 6 | 6 | 1 | 87 | 25 | 25 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 91 | 24 | 24 | 00 | 0.02 | | |
| 3 | 9 | 7 | 8 | 0 | 48 | 5 | 5 |
| ***T*** | ***0.*** | ***0.*** | ***0.*** | ***0.*** | | | |
| ***2*** | ***11*** | ***12*** | ***00*** | ***00*** | ***0.00*** | | |
| ***4*** | ***67*** | ***01*** | ***00*** | ***45*** | ***45*** | ***1*** | ***1*** |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 96 | 13 | 20 | 11 | 0.03 | | |
| 5 | 2 | 4 | 5 | 3 | 18 | 7 | 7 |
| T | 0.1 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 02 | 20 | 14 | 04 | 0.01 | | |
| 6 | 0 | 2 | 7 | 4 | 91 | 2 | 2 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 96 | 13 | 20 | 10 | 0.03 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | 7 | 9 | 0 | 8 | 08 | 6 | 6 |
| T | 0.1 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 01 | 19 | 15 | 05 | 0.02 | | |
| 8 | 3 | 4 | 4 | 3 | 06 | 3 | 3 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 2 | 94 | 11 | 22 | 13 | 0.03 | | |
| 9 | 7 | 6 | 0 | 1 | 51 | 9 | 9 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 3 | 99 | 17 | 17 | 07 | 0.02 | | |
| 0 | 6 | 4 | 1 | 2 | 43 | 4 | 4 |
| T | 0.0 | 0.1 | 0.0 | 0.0 | | | |
| 3 | 95 | 13 | 20 | 11 | 0.03 | | |
| 1 | 9 | 0 | 8 | 6 | 24 | 8 | 8 |

It is evident from Table 2 that from both methods, same trial runs occupy first and last rank respectively. However, there is a little bit difference in the rank of a few other trial runs which may be attributed to the procedural differences in different methods. Further, Table 2 also reveals that among all 31 trial runs, T24 is top ranked indicating the highest values of UTS (241.67 MPa) and η (95.52%). The optimized parameter combination is found to be rotational speed of 1,150 rpm, welding speed of 50 mm/min, axial force of 6 kN, and reinforcement of ZrB2 at 10 wt%. These values exactly matched with those suggested by Gadakh et al. [21] which proves the applicability, efficacy and flexibility of the SD based PIV method in solving MCDM problems.

## 5. CONCLUSIONS

This paper demonstrated the application of standard deviation (SD) based preference indexed value (PIV) method for the optimal selection of the friction stir welding (FSW) process parameters through an illustrative example.

The results obtained by this method are compared with those derived by past researcher using MOORA method and it is found that the optimal FSW process parameters are same from both the methods. Further, the ranking of almost all trial runs of the FSW is found to be the same which proves almost same performance of the two methods.

SD method can be used to accurately calculatethe criteria weights which are used in the PIV method for alternative ranking. PIV method can consider all attributes along with their relative importance, involves simple computational steps, and minimizes the alternatives' rank reversal problem and hence, it produces more robust and reliable results of the decision-making problems.

Moreover, in this method of ranking the alternatives the steps are independent of the length of decision matrix. Thus, it may be concluded that the method proposed in this paper is simple, efficient, and effective which can be used for getting accurate solutions to any type of selection problem.

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