Experimental and optimization studies of ultrasonic-assisted friction stir weldments of AA2014-T651 using graph theory

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Abstract
The present study focuses on development of mechanical characteristics in ultrasonic vibration assisted friction stir welding (UAFSW) of AA 2014-T651 weldment using graph theory algorithm and utility concept. A set of UAFSW experiments were carried out using plain and taper threaded cylindrical tool pin profile on AA 2014-T651 weldments at different levels of tool rotation speed and traverse speed and experimental results for the tensile strength, yield strength, percentage of elongation, impact strength, and micro hardness were collected. Microstructural studies were also made and correlated with the mechanical characteristics and found that the mechanical characteristics were increased. The process parameters were optimized by the proposed methodology as 1100 rpm of tool rotational speed and 40 mm/min of traverse speed. The tensile strength, yield strength, percentage of elongation, impact strength, and micro hardness were found to be 431.69 MPa, 307.47 MPa, 11.66%, 8.32 J, and 139 HV respectively at optimum working condition. The weld joint obtained using a taper threaded tool pin profiled tool with ultrasonic vibration possesses 90% of joint efficiency.

Keywords UAFSW · Mechanical characteristics · Microstructure · Graph theory · Tool rotation speed · Tool traverse speed

1 Introduction
The AA 2014-T651 alloy was developed with a wide range of applications in view, including transportation, aircraft, and applications [1]. The AA2014 is a difficult to weld because of high thermal diffusivity by conventional welding. To overcome these difficulties, friction stir welding (FSW) is a new processing technique, developed by Wayne Thomas at TWI in 1991, UK. Compare to conventional welding techniques, it reduced distortion, and defect rate, simplifies dissimilar alloy welding, eliminates consumables, and reduces health diseases and hazards and no weld pool. FSW has numerous advantages such as mechanical characteristics enhancement under welding, good protection to the welder, strong in welding, suitable for limited thickness materials [2–4]. FSW the weld takes place without fusion at the interface of the two parts to be welded and no filler metal is added [5]. During the FSW, the two metal are mixed by the stirring action of rotating tool at plasticization temperature. The heating is accomplished by friction between the workpiece and the tool, which provides the material to soften around the pin. The combination of a tool rotational speed (TRS) and its translation speed deform the material from the front of the pin to the rear of the pin and mixes thoroughly. The material goes through extreme plastic deformation, resulting in significant grain refinement during FSW [6]. Zhang and Zhang [7] reported that increased speeds, including TRS and traverse speeds (TTS), can both accelerate the material flow, particularly in front of the pin on the retreating side, where the material flow is quickest [7]. But the mechanical characteristics of weldments made by conventional FSW do not reach the base metal properties. Therefore, the present study focuses on development of FSW to improve mechanical characteristics in the weldments.

The effect of different pin features and orientation/placement of the materials on the advancing side were investigated for friction stir welding (FSW) of dissimilar aluminum alloys AA2050 and AA6061 are reported by Rezaet al. [8] and concluded that quality welds are produced by pin with thread +3 flats at low TRS and TTS.
Later, ultrasonic-assisted FSW (UAFSW) was proposed and found enhanced mechanical characteristics in the weldments with reduced axial welding forces [9, 10]. Usage of ultrasonic waves to tool has multiple effects like improving the weld quality, enhancing the processing speeds, along with a huge decrease in deformation forces [11]. Therefore, the researchers concentrated on implementation of UAFSW for various metals. Ultrasonic vibrations will improve mechanical characteristics by reducing shear stress and yield stress of materials. Process effectiveness of welding can be improved by ultrasonic vibrations as a supplementary energy to the process [12, 13]. Park et al. [14] conducted experiments and concluded that the ultrasonic vibrations improved the tool penetration, which reduces the axial force by about 25% and welding force up to 10%. Chawla et al. [16] proved that the strengthening of AMC is significantly affected by the microstructure of the aluminum matrix and reinforcement particles. For the studied BM in T6 metallurgical conditions (strengthened by strengthening precipitates), a higher traverse speed results in insufficient stirring time for complete recrystallization (producing a coarse grain structure). This, combined with the partial dissolution of the precipitates resulting from the FSW thermal cycles and subsequent re-prefusion during natural aging after FSW, results in an increase in strength [17]. Furthermore, according to the Taylor strengthening mechanism, volumetric strain occurs in the composite when using a fast cooling rate due to the thermal mismatch between the aluminum matrix and SiC particles which leads to the generation of geometrically necessary dislocations (GNDs) around the reinforcement particles [17, 18].

Liuet al. [19] carried out UAFSW experiments on AA 2014-T4 at two levels of TRS and TS with 20 kHz frequency and found improved weld quality and mechanical characteristics of the joint. Moradi et al. [20] conducted UAFSW experiments on dissimilar aluminum alloys AA6061-T6 to AA 2024-T3 and found improved plasticized material flow, eliminated the welding defects, and also improved the material bonding strength at joint. The ultrasonic vibrations exerted to the rotating tool by sonotrode in two directions, i.e., axial direction and welding directions. During the UAFSW, the ultrasonic vibrations are directly transferred to the workpiece and eliminate the energy losses [21]. Ultrasonic vibrations exerted into the welding direction was firstly introduced by Park et al. [22] and observed an enhancement of material properties. Ruilin et al. studied the effect of the welding speed along with ultrasonic vibrations on the weld quality and concluded that the ultrasonic vibrations are not effective at lower welding speeds [23]. Ji et al. introduced a new ultrasonic vibration system for FSW of Mg and Al alloys and found better mixing of alloys as well as improved the toughness, elongation, and tensile strength of the joint [24]. However, still it is required to improve mechanical characteristics and better mixing of two metals during the process by selecting optimal working conditions.

Researchers have used different optimization techniques to process parameters optimization to maximize the mechanical characteristics. A conventional approaches like design of experiments [25], Taguchi method [26], particle swarm optimization [27], relation analysis [28], genetic algorithm [29], ant colony algorithm [27], and the multi-objective biogeography-based optimization algorithms are widely used in the FSW process and improved the mechanical characteristics [30, 31]. However, the mentioned approaches were not able to handle complex optimization problems, since they give equal weightage to the responses.

The existing literature summarized the need to develop novel methods to improve the mechanical characteristics to a certain value in relation to the application of welding. The proposed methodology named as graph theory and utility certificate (GTUC) estimates weights to the responses scientifically considering opinions of different users [32] to improve mechanical characteristics accordingly. In the present study, the work piece is vibrated at ultrasonic frequency of 20,000 Hz with an amplitude of 4 µm and experiments were carried out at different levels of tool rotational speed and traverse speed. In addition, the process parameters were optimized by novel optimization concept (GTUC). The process parameters were optimized using the proposed methodology to achieve better mechanical characteristics of UAFSW of AA 2014-T651 weldments.

2 Experimental procedure

The present study was carried out in two phases; in the first stage, the workpieces of AA2014-T651 sizes of 140×60×6 mm were welded by UAFSW on vertical milling machine. A specially designed tool namely plain cylindrical taper tool (PCT) and taper threaded cylindrical tool pin (TCT) profiles are used to produce strong weldments. Based on the previous researches, capacity of machine, tool, and workpiece, the process parameters were selected from the ranges of 600 rpm ≤TRS ≤1200 rpm, 30 mm/min ≤TTS ≤70 mm/min. The schematic representation of UV setup consists of Generator, Convertor, Booster, and Horn was shown in Fig. 1.

The Ultrasonic Generator is a solid electronic box, which feeds 220 V and 50 Hz, 15 A from the mains. The ultrasonic power supply converts 50/60 Hz voltage to high-frequency (20 kHz) electrical energy. This high-frequency current is
then transmitted to the ultrasonic stack via a special cable. Ultrasonic stack is a combination of three core components, i.e., the converter, booster, horn. The horn receives vibrations from the booster with frequency more than 20 kHz. In the present study, amplitude the vibration was fixed as 4 µm. As shown in Fig. 2, the ultrasonic waves are transmitted directly into the workpiece without impacting its exterior of the workpiece. As per design of experiments presented in Table 1, eighteen experiments were conducted on AA2014-T651 weldments (shown in Fig. 3) using the plain and taper threaded cylindrical tool pins at three levels of TRS (700, 900, and 1100 rev/min) and three levels of TTS (40, 50, and 60 mm/min) with 1.5° of constant tool tilt angle.

The AA2014-T651 manufactured welds are cross-segmented transitionally to the welding direction according to ASTM-E8 and A370 specifications using the wire electrical discharge machining. To test mechanical characteristics, the samples were cleaned at the surface and edges to prevent stress concentration [31]. Figure 4 displays the schematic diagram for the tensile and Impact specimens. Samples of scale 10×10 mm have been sectioned from stir zone of FSWed specimens for optical metallography. The samples were placed by Bakelite powder with 2 min of heating and 6 min of cooling time by applying pressure. The specimens were prepared according to the standards of Al alloys and etched with a mixture of 2 ml of HF, 3 ml of HCL, 5 ml of HNO₃, and 190 ml of distilled water for 30–60 s to expose the microstructure. The method of conventional linear intercept has been carried out to measure the grain size [18].

The microhardness was measured at the stir zone using a digital microhardness tester (HVS-100B model). A universal testing machine was used for the tensile test at a crosshead speed of 0.5 mm/min with 100 kN capacity at room temperature. Izod impact tester was used for measuring the weld impact strength.

In the second stage, process parameters are optimized to improve mechanical characteristics using graph theory and utility concepts. In this stage, the weights are calculated using the experimental data by keeping the tensile strength (TS), yield strength (YS), percentage of elongation (EL), impact strength (IS), and hardness (H). New process variables and their corresponding responses are obtained using the utility concept and obtain the best solutions based on the rank.
3 Results and discussion

The material flow and temperature generation during the weld were influenced by UAFSW process parameters, thereby influencing the microstructural evolution of the material. This microstructural modification of the material leads to the enhancement of characteristics. Since the present study aims to maximize the mechanical characteristics of weldments, the process parameters are optimized by graph theory, and the utility concepts are illustrated in this section.

Table 1 Mechanical characteristics of friction stir AA2014 weldments with UV

| Tool pin profile | Design of experiments | TS (MPa) | YS (MPa) | EL (%) | IS (J) | H (HV) | Joint strength (%) |
|------------------|-----------------------|----------|----------|--------|--------|--------|-------------------|
|                  | TRS (rev/min) | TTS (mm/min) |
| PCT tool pin profile | 700 | 40 | 329.67 | 269.73 | 9.10 | 7.57 | 111 | 68 |
|                  | 700 | 50 | 313.02 | 266.40 | 8.51 | 6.80 | 108 | 64 |
|                  | 700 | 60 | 296.37 | 263.07 | 7.91 | 6.04 | 105 | 61 |
|                  | 900 | 40 | 344.10 | 270.84 | 9.09 | 7.68 | 114 | 71 |
|                  | 900 | 50 | 327.45 | 267.51 | 8.52 | 6.92 | 112 | 67 |
|                  | 900 | 60 | 310.80 | 265.29 | 7.96 | 6.16 | 109 | 64 |
|                  | 1100 | 40 | 357.42 | 271.95 | 9.14 | 7.80 | 117 | 73 |
|                  | 1100 | 50 | 340.77 | 269.73 | 8.61 | 7.05 | 115 | 70 |
|                  | 1100 | 60 | 324.12 | 266.40 | 8.01 | 6.29 | 113 | 67 |
| TCT tool pin profile | 700 | 40 | 370.74 | 284.16 | 8.66 | 6.76 | 129 | 76 |
|                  | 700 | 50 | 341.88 | 238.65 | 7.55 | 6.03 | 125 | 70 |
|                  | 700 | 60 | 313.02 | 194.25 | 6.55 | 5.30 | 122 | 64 |
|                  | 900 | 40 | 379.16 | 295.26 | 10.10 | 7.59 | 133 | 78 |
|                  | 900 | 50 | 366.30 | 250.86 | 9.10 | 6.86 | 130 | 75 |
|                  | 900 | 60 | 338.55 | 206.46 | 7.99 | 6.24 | 126 | 69 |
|                  | 1100 | 40 | 431.69 | 307.47 | 11.66 | 8.32 | 139 | 90 |
|                  | 1100 | 50 | 392.94 | 263.07 | 10.66 | 7.80 | 136 | 81 |
|                  | 1100 | 60 | 364.08 | 217.56 | 9.55 | 7.07 | 131 | 75 |
| Base metal | | | | | | | |
|                  | 485 | 413 | 13 | 9 | 155 | | |

Fig. 3 Surface morphology of UAFSW weldments fabricated by (i) PCT and (ii) TCT

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3.1 Mechanical characteristics

The evaluated mechanical characteristics of AA2014-T651 UAFSWed weldments are presented in Table 1. The weldments fabricated by the taper threaded pin profile tool in UAFSW at 1100 rev/min of the rotation speed and 40 mm/min of traverse speed of tool exhibited higher tensile characteristics with a joint efficiency \((\frac{\text{Tensile strength of the sample made by UAFSW process}}{\text{Parent metal tensile strength}})\) of 90% compared to plain cylinder pin profile tool at various conditions. This is owing to the compressive forging force on the weld, thorough mixing of the material, and also proper material flow due to the influence of ultrasonic vibrations during the welding. Hence, the welds obtained with higher stirring and mixing action of the tool leads to high strength in the stir zone while simultaneously keeping a notable extent of ductility. This is in agreement with the Hall–Petch strengthening mechanism, as grain refinement and the formation of a high fraction of HAGBs leads to the increase of the resistance to the motion of dislocation and pile-up of dislocations at grain boundaries, which plays a significant role in enhancing resistance to plastic flow [17]. The percentage of elongation is also higher in the weldments fabricated with a threaded taper cylindrical tool pin profile compared to a plain taper cylindrical profiled tool pin. This may be due to the increased resistance to deformation of the welded weldments which is due to the microstructural changes in the stir zone shown in Fig. 7g.

In FSW, the material flow on the upper side of the friction stir weld can be accelerated by the shoulder. The material in the nugget zone can be more completely mixed by increasing the angular velocity of the pin, which enhances the joining quality of the two welding plates. Increased speeds, including rotational and translational speeds, can both accelerate the material flow, particularly in front of the pin on the retreating side, where the material flow is quickest, which results in improved mechanical characteristics [7]. Similarly, Salih et al. also concluded improved tensile strength of FSW joints with an increased mean grain size at lowest tool rotation speed. However, at higher tool rotation speed, the tensile strength of weldments goes through a maximum with a higher traverse speed as a result of the evolution of entirely recrystallized finer grain [16, 17].

The mechanical characteristics are evaluated in different stages of FSW (i.e., base metal, plain taper cylindrical profile tool without ultrasonic vibration, taper threaded cylindrical profile tool without ultrasonic vibration, plain taper cylindrical profile tool with ultrasonic vibration, and taper threaded cylindrical profile tool with ultrasonic vibration) and are presented in Table 2.

The material around the pin is considerably softer with the application of ultrasonic vibration and can withstand reasonable plastic deformation due to the acoustic elastic effect, resulting in the formation of lamellar structures alternating from fine grain and coarse grain. The breakdown of metastable platelets and their re-precipitation appear in SZ [33]. The geometrical dislocation density is associated with the grain size, and regarding fine-grained structure, the geometrical dislocations principally affect the density of dislocations in thermomechanical processing which modify the plastic deformation among grains [18]. In UAFSW, formation of fine grain structure in the stir zone is attributable to dynamically recrystallization and thermal exposure. Because of the intense heat generated while processing, the material attains the plastic state. The tool stirring action on the metal in the stir zone disintegrates the coarse and elongated grains into smaller grains. Hence refined microstructure is found along with the enhanced mechanical properties. Therefore, the mechanical characteristics in the weldments are found to be closed to base metal properties.

The microhardness values of the base metal and the UAFSW weldments are presented in Table 1. The maximum value of hardness is 139 HV obtained at the stir zone (SZ) for
the weldments fabricated by threaded taper pin profile tool at 1100 rev/min as the rotation speed of a tool and 40 mm/min as tool traverse speed due to grain refining through dynamic recrystallization [34] and influence of ultrasonic vibrations. The UAFSW joint hardness of two tool pin profiles exhibit asymmetric distribution with a typical W shape for all joints [17]. It is believed that this variation in the hardness of SZ is a result of the difference of microstructures characterizations, which are controlled by welding parameters [17]. Figure 5 presents the microhardness distribution of UAFSW weldments for PCT and TCT from both sides, i.e., retreating and advanced of the HAZ, TMAZ, and SZ were provided at 1100 rpm with traverse speed of 40 mm/min, associated with a higher peak temperature and exposure time. Regardless of the welding parameters, a softening process occurred in the SZ, and the hardness value of the BM was much higher than that of the SZ shown in Table 1. The transition between HAZ and TMAZ obtain a minimum value of hardness due to grain refining through dynamic recrystallization and the influence of ultrasonic vibrations [34, 35].

### 3.2 Microstructure

The microstructures of the weldments were examined at the weld region of friction stir weldments using taper cylindrical tool pin profile and without ultrasonic vibration. The inconsistency revealed significantly unique microstructure in the SZ produced by plain taper cylindrical and taper threaded profile tool with ultrasonic vibration as shown in Figs. 6 and 7. It is experimental that the weldments fabricated by the TCT (Fig. 7g) resulted in a high reduction in the size of grains and the formation of equiaxed grains in the weldments [36]. The grain size difference is attributed to the joint temperature, strain rate, and stir action during the joining process. It has been known that continuous and discontinuous dynamic

| Weld condition                           | UTS (MPa) | YS (MPa) | %EL  | Micro hardness (HV) | Impact toughness (J) |
|------------------------------------------|-----------|---------|------|---------------------|----------------------|
| PCT without ultrasonic vibration        | 322       | 245     | 8.23 | 109                 | 7.5                  |
| TCT without ultrasonic vibration        | 379       | 277     | 10.5 | 129                 | 8                    |
| PCT with ultrasonic vibration           | 357       | 271     | 9.14 | 117                 | 7.8                  |
| TCT with ultrasonic vibration           | 431       | 307     | 11.6 | 139                 | 8.3                  |
| Base metal                               | 483       | 414     | 13   | 155                 | 9                    |

Fig. 5 Microhardness distribution of UAFSW weldments for PCT and TCT
Recrystallizations (CDRX and DDRX) are the fundamental mechanisms with respect to the modification of grains during friction stir welding [37, 38] and also the density of dislocations increases during FSW by severe plastic deformation. During UAFSW, the material deformation in the stir zone because of vibration is higher in comparison with that during FSW. Better deformation leads to a higher density of dislocations. Therefore, dynamic recrystallization develops, and finer grains, with respect to FSW, increase [39]. The recrystallization of grains in aluminum happens because of the dynamic recrystallization, which is driven by heat and cooling rate [40].
Fig. 7 Microstructures of weldments fabricated by UAFSW with TCT. a 700 rev/min; 40 mm/min, b 700 rev/min; 50 mm/min, c 700 rev/min; 60 mm/min, d 900 rev/min; 40 mm/min, e 900 rev/min; 50 mm/min, f 900 rev/min; 60 mm/min, g 1100 rev/min; 40 mm/min, h 1100 rev/min; 50 mm/min, i 1100 rev/min; 60 mm/min, and j base metal
This is due to the frictional force exerted, severe stirring action by the friction stir tool, optimum heat generation with the influence of ultrasonic vibrations, and the friction-dominated flow of material was observed [21] at the microstructure which leads to the formation of fine aluminum grains at the SZ. Whereas the weldments produced TCT profile showed equiaxed and finer grains with 4.11 μm of mean grain size, at weld nugget by tool traverse speed of 40 mm/min and TRS of 1100 rev/min. Here, ultrasonic vibrations influenced the process which attributes to the greater straining of the metal resulting from process parameters, which causes more strain-free nucleation sites, providing sufficient frictional heating in the SZ. The good stirring action between the tip and collar, and avoids the turbulence which resulted in better mechanical characteristics of the joint. The weldments made by PCT with UAFSW resulted in a great reduction of 5.05 μm in the size of grains which is less than the welded samples at the SZ of the PCT at the same condition. This is due to better mixing of material and finest heat generation due to the influence of ultrasonic vibrations.

3.3 Fractography

Fracture surface analysis of tensile specimens of the UAFSW of AA2014-T651 weldments made by different tools such as PCT and TCT pin profiles with different rotation speeds and traverse speeds of the tool were shown in Figs. 8 and 9. However, during the tensile test, the specimens were fractured where the hardness value is the lowest, i.e., retreating side, which was also examined with the hardness measurement [34]. Weldments made by taper threaded pin profile tool with ultrasonic vibrations exhibited superior ductility (Fig. 9g) as compared with the weldments made by plain taper tool pin profile with ultrasonic vibrations. This is because of the presence of small shallow dimples furthermore some huge dimples that resulted in micro dimples coalescence. It could be attributed to the high plastic deformation which indicates a more intense ductile fracture.

Fracture surface analysis of impact specimens of the UAFSW of AA2014-T651 weldments made by PCT and TCT with different TRS and TTS was shown in Figs. 10 and 11. The impact fracture surface of a taper threaded tool pin profile (Fig. 11g) shows large and fine dimples, which could be attributed to the better impact strength of the weldments.

3.4 Optimization

In the second phase, the process parameters were optimized by graph theory, and utility concept to maximize the mechanical characteristics of weldments.

3.4.1 Graph theory algorithm

In the present study, weights to the mechanical characteristics scientifically using opinions of different users. There is no limitations on the number of users, based on the applications of joints in using all the joints may not be having similar properties. That is why opinions of the different users were collected based on their requirements. Weights to the mechanical characteristics are calculated using six steps.

Step 1: Preference graph based on client

A preference graph is developed from the assessments of various investigations and manufacturers [41]. As displayed in Fig. 12, the assessments of five distinct clients are gathered. Based on the assessments of the clients, the characteristics are given priority from high to low as follows:

(i) The first client has given topmost priority to the hardness value and followed by the values of impact strength, percentage of elongation, yield strength, and tensile strength.
(ii) The second client has given high priority to the values of yield strength and percentage of elongation equally followed by the tensile strength, impact strength, and hardness values.
(iii) The third client has given topmost priority to yield strength and percentage of elongation characteristics equally followed by tensile strength, hardness, and impact strength characteristics.
(iv) The fourth client has given high priority to the percentage of elongation followed by yield strength, impact strength, tensile strength, and hardness.
(v) The fifth client has given high priority to hardness followed by the percentage of elongation, yield strength, tensile strength, and impact strength.

Step 2: Matrix of preference

The transpose of the coefficient matrix is constructed and presented below according to preference graphs.

\[ PG_n = [p_{gij}]_{MxM} \]  

Where the client’s count was represented with n, and Responses represented with M, and \( p_{gij} \) gives the dominance of i over j in an MxM.
Fig. 8 Fracture surface resultant from tensile test of UAFSW with PCT: a 700 rev/min; 40 mm/min, b 700 rev/min; 50 mm/min, c 700 rev/min; 60 mm/min, d 900 rev/min; 40 mm/min, e 900 rev/min; 50 mm/min, f 900 rev/min; 60 mm/min, g 1100 rev/min; 40 mm/min, h 1100 rev/min; 50 mm/min, i 1100 rev/min; 60 mm/min, and j base metal.

- Voids
- Large dimples
Fig. 9 Fracture surface resultant from tensile test of UAFSW with TCT: a 700 rev/min; 40 mm/min, b 700 rev/min; 50 mm/min, c 700 rev/min; 60 mm/min, d 900 rev/min; 40 mm/min, e 900 rev/min; 50 mm/min, f 900 rev/min; 60 mm/min, g 1100 rev/min; 40 mm/min, h 1100 rev/min; 50 mm/min, i 1100 rev/min; 60 mm/min, and j base metal.
Fig. 10 Fracture surface resultant from impact test of UAFSW with PCT: a 700 rev/min; 40 mm/min, b 700 rev/min; 50 mm/min, c 700 rev/min; 60 mm/min, d 900 rev/min; 40 mm/min, e 900 rev/min; 50 mm/min, f 900 rev/min; 60 mm/min, g 1100 rev/min; 40 mm/min, h 1100 rev/min; 50 mm/min, i 1100 rev/min; 60 mm/min, and j base metal
Fig. 11 Fracture surface resultant from impact test of UAFSW with TCT: a 700 rev/min; 40 mm/min, b 700 rev/min; 50 mm/min, c 700 rev/min; 60 mm/min, d 900 rev/min; 40 mm/min, e 900 rev/min; 50 mm/min, f 900 rev/min; 60 mm/min, g 1100 rev/min; 40 mm/min, h 1100 rev/min; 50 mm/min, i 1100 rev/min; 60 mm/min, and j base metal.
Step 3: Dominance matrix D:

Among all the performance characteristics more preferred performance characteristics were identified by the D matrix.

\[ D^p = \sum_{j=1}^{M} PG_j \]

Also,

\[ d^m_n = \sum_{j=1}^{M} PG_j \]

where the client’s count was represented with \( n \), and Responses represented with \( M \).

The D matrix was calculated using the Eq. (2), where \( m \) value was taken as 5 then:

\[
D_{pg1} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0
\end{pmatrix}
\]

\[
D_{pg2} = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
D_{pg3} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
D_{pg4} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
D_{pg5} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

Step 4: Relative degree of performance (RDP)

The RDP addresses represent relative assessment among the five mechanical characteristics of a similar preference graph between 0 and 1. The RDP was controlled by utilizing condition (3).

\[
RDP^m_n = \frac{1 + d^m_n}{\text{Max}_m = 1 \ldots M^1 + d^m_m}
\]

| \( R_{Dpg1} \) | \( D_{pg1} \) | \( R_{Dpg} \) | \( D_{pg2} \) | \( R_{Dpg3} \) | \( D_{pg3} \) | \( R_{Dpg} \) |
|---|---|---|---|---|---|---|
| 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 |
| 1 1 1 1 0 1 | 1 0 0 1 1 1 | 1 0 0 1 1 1 | 1 0 0 1 1 1 | 1 0 0 1 1 1 | 1 0 0 1 1 1 | 1 0 0 1 1 1 |
| 0 1 1 1 0 0 0 | 1 0 0 1 1 1 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 |
| 0 0 1 1 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 |
| 0 0 0 1 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 | 0 0 0 0 0 |
Step 5: Relative importance rating (RIR):

The RIR was determined by joining the five mechanical characteristics of RDPs utilizing the underneath Eq. (4).

\[
RIR_m = \frac{\sum_{n=1}^{N} rdp_m^n}{\text{Max } m = 1 \ldots M} \sum_{n=1}^{N} rdp^n_m
\]

Step 6: Weight of responses (W):

Weights of five responses are calculated as follows:

\[
W_m = \frac{RIR_m}{\sum_{m=1}^{M} RIR_m}
\]

Then the weights of responses such as TS, %EL, YS, IS, and H are calculated as 0.1777, 0.2222, 0.2222, 0.1888, and 0.1888 respectively.

\[
W_m = (0.1777, 0.2222, 0.2222, 0.1888, 0.1888).
\]

3.4.2 Utility concept

In the utility concept method, the experimental results, preference scales, and weights using to estimate the utility value.
This was calculated for five responses for the 9 readings using the below condition.

\[ U(n, y) = P_{TS}(n, y) \times W_{TS} + P_{YS}(n, y) \times W_{YS} + P_{\%EL}(n, y) \times W_{\%EL} + P_{IS}(n, y) \times W_{IS} + P_{H}(n, y) \times W_{H} \]

where the pass number is indicated with n and the repetition number is indicated with y. Similarly, W is the weight, and the preference scale was represented with P.

The utility value of all mechanical characteristics was evaluated using the following Eq. (7); here, a preference scale is mandatory. The \( P \) value was chosen as 0 to 9 based on the acceptable level”.

\[ P = A \log \frac{x_i}{x_j} \]

where the value attribute response is the value of \( x_i \), the maximum acceptable value is \( x_j \) of mechanical characteristics and A is the constant. In this work, the maximum acceptable levels for TS, YS, %EL, IS, and H are taken as 431.69 MPa, 307.47 MPa, 11.66%, 8.32 J, and 139 HV respectively. The five responses of attributes are estimated using MINITAB 2019. Preference scales for the mechanical characteristics are calculated as follows:

Preference scale for tensile strength (TS):

\[ P_{TS} = -184.52 \log \frac{X_{TS}}{483} \]

Preference scale for yield strength (YS):

\[ P_{YS} = -69.66 \log \frac{X_{YS}}{414} \]

Preference scale for percentage of elongation (%EL):

\[ P_{\%EL} = -190.49 \log \frac{X_{\%EL}}{13} \]

Preference scale for impact strength (IS):

\[ P_{IS} = -266.59 \log \frac{X_{IS}}{9} \]

Overall utility value for taper threaded cylindrical tool pin profile was calculated using Eq. (6) and presented in Table 3.

From Table 3, one best combination of the process parameters, which is having the first rank, is selected as the optimum combination of TRS and TTS. Based on these combinations, setup experiments were done for validation of the process.

Similarly, the graph theory and utility concept was implemented for the plain cylindrical tool pin profile. However, the TCT profile with ultrasonic vibrations exhibits better mechanical characteristics compared to the PCT profile.

### 3.5 Validation of optimization

To check the responses, the validation experiment is carried out at an optimal combination of TRS and TTS. The normal utility value predicted at the optimal combination of the TRS and the TTS was found to be 8.9145, and it is within the anticipated range of 500 rpm to 1500 rpm of tool rotation speed, and 30 mm/min to 70 mm/min. The five responses were also predicted at the same optimal combination of process parameters. The anticipated values and experimental values of the five responses were well fit within the anticipated optimal range by a 99% of R-Sq value.

### 4 Conclusions

In the present study, influence of process parameters such as tool rotation speed, tool traverse speed, and ultrasonic vibration on mechanical characteristics of weldments
was studied. The work was done in two stages: in the first stage, the experimentation was carried out using ultrasonic vibration, and in the second stage, the process parameters were optimized using graph theory and utility concept. From the investigation, the following important conclusions have been derived:

- The weld joint obtained using threaded taper tool pin profile with ultrasonic vibration possesses 90% of joint efficiency compared to the weldments made by PCT with ultrasonic vibration. It was found that good stirring action from the tip to the collar eliminated the turbulence.
- Joints fabricated by a plain taper cylindrical tool pin profile at a tool rotation speed of 1100 rpm, weld speed of 40 mm/min exhibited better mechanical characteristics, as a result of f entirely recrystallized finer grains. This is due to the intense plastic deformation and sufficient frictional heat generation in the stir zone, and also proper material flow due to the influence of ultrasonic vibrations.
- Weights for the TS, YS, %EL, IS, and H were found as 0.1777, 0.2222, 0.2222, 0.1888, and 0.1888 respectively using graph theory. The graph theory and utility concept optimized the process parameters as 1100 rpm of TRS and 40 mm/min of TTS.
- The tensile strength, yield strength, percentage of elongation, impact strength, and micro hardness were found to be 431.69 MPa, 307.47 MPa, 11.66%, 8.32 J, and 139 HV respectively at optimum working condition. This is due to the compressive forging force on the weld, thorough mixing of the material, and also proper material flow due to the influence of ultrasonic vibrations during the welding.
- The highest impact strength of 8.32 J, hardness value of 139 HV were observed at the stir zone of the weldments fabricated by a threaded taper cylindrical tool pin profile compared to the plain taper cylindrical tool pin profile. This is due to grain refining through dynamic recrystallization and the influence of ultrasonic vibrations.
- The microstructure at the stir zone of UAFSW weldments using a threaded taper cylindrical tool pin profile contains fine grains. This is due to the influence of ultrasonic vibrations which attributes to the higher straining of the metal resulting from process parameters, which causes more strain-free nucleation sites, provides sufficient frictional heating in the stir zone.

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**Data availability** The data supporting the findings of this study are available within the article.

**Code availability** Not applicable.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

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**Conflict of interest** The authors declare no conflict of interest.

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