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Hybrid CRITIC-VIKOR-Taguchi method of evaluating mechanical properties of magnesium alloy welded joint with cerium powder addition at weld interface

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Abstract

Magnesium alloys reactivity with oxygen is very high and produce more defects when welded by employing fusion welding processes. Solid state welding processes do not melt the material and hence the problem can be reduced to a greater extent. Friction stir welding (FSW) is one of the solid state welding processes has gained popularity, of late, due to higher productivity coupling to achieve superior mechanical properties. In the present research, a hybrid CRITIC–VIKOR–Taguchi framework was developed in tackling the multi criterion decision making issues. Taguchi method was employed for selection of experimental matrix efficiently, while the CRITIC (Criteria Importance Through Intercriteria Correlation) method was used to objectively determine the relative weights to the responses under consideration. Subsequently, the VIKOR multi-criteria decision-making technique was applied to identify the optimum welding conditions based on Taguchi technique. The proposed methodology simultaneously considered ultimate tensile strength (UTS), impact toughness, and microhardness as the key performance characteristics. At optimal parameter condition the UTS is 103MPa, Impact toughness is 1.63J while micro hardness is 6.95Hv. The tool rotational speed is governing the achievement of responses to the extent of 47.83%, weld speed is contributing by 18.73% while tool tilt angle is to the tune of 10.51%. Microstructural characterization using scanning electron microscopy revealed significant grain refinement within the stir zone, contributing to enhanced mechanical performance and improved joint integrity. The results demonstrate that the proposed hybrid CRITIC–VIKOR–Taguchi approach effectively balances multiple conflicting performance objectives and provided an optimal solution.

Keywords: *Friction Stir Welding, AZ91D Magnesium Alloy, Hybrid Optimization, CRITIC-VIKOR-Taguchi, Mechanical Properties.*

1.0 Introduction

Magnesium alloy AZ91D has been increasingly employed in the automotive, aerospace, and biomedical industries owing to its high strength-to-weight ratio, excellent castability, machinability and damping characteristics. Despite these advantages, the alloy exhibits limited ductility and is vulnerable to defects caused by excessive heat input during fusion welding processes [1]. Friction Stir Welding, a solid-state joining process, has emerged as better alternative for joining magnesium alloys; It avoids melting during welding, there by avoids the formation of defects such as porosity, hot cracking, and solidification defects [2]. Furthermore, the severe plastic deformation and dynamic recrystallization occurring during FSW produce refined grain structures that significantly enhance the mechanical properties of the welded joints. The quality of FSW joints is primarily governed by process parameters such as tool rotational speed, welding speed, and tool tilt angle, which directly influence heat generation, material flow, and microstructural evolution; As a sequel to this the responses ultimately affecting ultimate tensile strength (UTS), impact toughness and microhardness are thoroughly improved [3–5].

The investigations examined the influence of rotational speed and traverse speed on the mechanical behaviour and microstructure of dissimilar AA6061/AZ31 FSW joints, manifested that appropriate parameter selection is essential for producing defect-free welds with superior mechanical properties [5]. Though considerable progress has been achieved in identifying the optimal combination of FSW parameters, various interactions among thermal cycles, material flow, and dynamic recrystallization mechanisms compelled to perform the characterisation of welded joints at the job specific conditions [6–8].

The approaches by Taguchi, response surface Methodology, Factorial technique etc are effective in reducing the number of experimental trials , but with a limitation of single-objective optimization and cannot adequately address multiple, conflicting performances simultaneously. Therefore, Multi-Criteria Decision-Making (MCDM) techniques have been employed for evaluating and optimizing manufacturing processes involving multiple performance characteristics. Among the available MCDM methods, the VIKOR technique has received considerable attention because of its ability to determine compromise solutions by simultaneously considering group utility and individual regret. The method effectively ranks alternative process conditions according to their proximity to the ideal solution, making it suitable for problems involving conflicting objectives [9]. However, the performance of the VIKOR method strongly depends on the weighting assigned to each evaluation criterion. Subjective weighting methods may introduce

decision bias, leading to inconsistent optimization results. To overcome this limitation, the Criteria Importance Through Intercriteria Correlation (CRITIC) method has been recognized as an effective objective weighting technique and determines criterion weights based on the variability of experimental data and the degree of conflict among evaluation criteria. It objectively quantifies the relative importance of each mechanical property without relying on any other condition and improve the reliability of the decision-making process [10–13].

The integration of the CRITIC and VIKOR methods provides a comprehensive and reliable framework for multi-objective evaluation and optimization. In the hybrid CRITIC–VIKOR approach, the CRITIC method first determines the objective weights of the mechanical performance indicators based on statistical characteristics of the experimental data. These weights are subsequently incorporated into the VIKOR algorithm to rank the experimental alternatives and identify the optimum compromise solution that simultaneously satisfies multiple conflicting responses. The investigations have demonstrated that hybrid CRITIC-based MCDM frameworks improved optimization performance in manufacturing processes, material selection, machining, and welding applications [14–18].

The present study employs a hybrid CRITIC–VIKOR approach to evaluate and optimize the mechanical properties of friction stir welded AZ91D magnesium alloy. Ultimate tensile strength, impact toughness, and microhardness are considered simultaneously as the primary performance criteria for assessing weld quality. The proposed methodology objectively determines the importance of each response using the CRITIC method and subsequently applies the VIKOR technique to identify the most suitable welding condition based on a compromise solution. Taguchi Orthogonal array is selected as design of experimental matrix. The integrated framework provides a systematic, objective, and reliable decision-support methodology for multi-response evaluation of friction stir welded magnesium alloys and offers valuable guidance for improving weld performance.

2.0 Materials

Magnesium alloy AZ91D is one of the most widely used cast magnesium alloys due to its excellent combination of low density, high specific strength, good castability, and satisfactory corrosion resistance. AZ91D possesses a low density of approximately 1.81 g/cm³, making it nearly one-third lighter than steel and significantly lighter than aluminum alloys. This lightweight characteristic makes it highly attractive for applications where weight reduction is essential, particularly in the automotive, aerospace, and electronics industries. The alloy also exhibits good vibration damping capacity, excellent machinability, and high dimensional stability, which further enhance its suitability for

engineering components. The chemical composition of the material employed for current investigation is given in Table.1., and the base metal microstructure is shown in Figure.1.

Table.1. Chemical Composition

Element	Mg	Al	Zn	Si	Mn	Cu	Fe	O
Composition	90.2	8.7	0.95	0.035	0.05	0.003	0.01	0.05

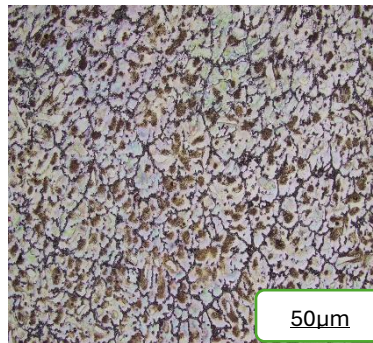


Figure.1. Microstructure of base metal

Cerium particles of 200µm size are employed at the plates interface before the joining process. The particles have FCC crystal structure and are locked between the plates by creating 1mm groove such that the spillage does not occur during welding process.

The microstructure of base material and weld joint are captured by Olympus optical microscope, while fracture features are examined by scanning electron microscope. The base material microstructure exhibits elongated grain of α -phase and metallic compounds.

3.0 FSW Parameters

Friction Stir Welding (FSW) is a solid-state joining process in which the quality and mechanical performance of welded joints are strongly influenced by the selection of appropriate process parameters. The welding parameters Table.2. control heat generation, material flow behaviour, plastic deformation, and microstructural evolution within the weld zone. For magnesium alloys such as AZ91D, proper optimization of these parameters is essential to achieve defect-free joints with improved mechanical properties.

100

Table.2.FSW Parameters

Process Parameters	Low values(1)	Higher values(2)
X₁(Speed in r.p.m)	710	1100
X₂(Feed in mm/min)	16	25
X₃(Tilt angle in Degrees)	2	3

101 **4.0 L8 Taguchi OA**

102 The Taguchi design of experiments (DOE) method is a statistical approach widely used for optimizing process
 103 parameters by reducing the number of experimental trials while maintaining reliable information about the effects of
 104 input variables on output responses. Among the various Taguchi orthogonal arrays, the L8 orthogonal array (OA) is
 105 commonly employed for experiments involving multiple parameters at two levels. For friction stir welding (FSW)
 106 optimization of AZ91D magnesium alloy, the L8 OA is suitable when three major welding parameters, such as tool
 107 rotational speed, welding speed, and tool tilt angle, are considered at two different levels Table.3.

108 **Table.3. Matrix of L8 Taguchi OA**

Experiment No.	Rotational speed(X ₁)	Feed(X ₂)	Tilt Angle(X ₃)
1	710	16	2
2	710	16	3
3	710	25	2
4	710	25	3
5	1100	16	2
6	1100	16	3
7	1100	25	2
8	1100	25	3

109

110 **5.0 Experimental Results& Analysis**

111 Friction Stir Welding (FSW) of AZ91D magnesium alloy with cerium powder (CeO₃) addition at the weld interface is
 112 an emerging approach to improve the mechanical performance and microstructural stability of welded joints. During

FSW, the rotating tool generates frictional heat and severe plastic deformation, which promotes material mixing and dynamic recrystallization within the stir zone. When cerium is introduced at the weld interface, it acts as a grain-refining and strengthening element during the thermomechanical process. The distributed Ce particles or Ce-containing phases can influence the microstructural evolution by restricting grain growth and promoting the formation of finer equiaxed grains.

The experimental results of the experiment are given in Table.4.

Table.4. Mechanical Properties with Cerium powder addition

Run	Ultimate Tensile Strength (UTS) N/mm ²	Impact strength (I _s) Joules	Hardness(Hv)
1	108.5	1.5	73
2	102.0	1.6	70
3	86.5	1.4	65
4	103	1.5	72
5	80.0	2.0	63
6	123.5	1.0	77
7	96.5	1.2	68
8	81.5	1.8	64

5.1 CRITIC Weighing Method

5.1.1.Normalization

For the CRITIC weighting method, the experimental responses (UTS, impact strength, and hardness) are first normalized (Table.5) because they have different units and magnitudes. Since all three responses are beneficial criteria (higher values indicate better weld performance), equation (1) is employed for normalization.

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad (1)$$

where x_{ij} is the experimental value of the i^{th} alternative, and x_j^{max} and x_j^{min} are the maximum and minimum values of the corresponding criterion.

Table.5.Normalized Values of Results

Run	Ultimate Tensile Strength (UTS) N/mm ²	Impact strength (I _s) Joules	Hardness (Hv)
1	0.5926	0.5000	0.7143
2	0.4444	0.6667	0.5000
3	0.0926	0.3333	0.1429
4	0.4677	0.5000	0.6429
5	0.0000	1.0000	0.0000
6	1.0000	0.0000	1.0000
7	0.3194	0.1667	0.3571
8	0.0342	0.8333	0.0714

5.1.2. Standard Deviation (σ_j)

For the CRITIC weighting method, the standard deviation (σ_j) of each normalized criterion is calculated to measure the contrast intensity (variability) of each mechanical property (Table.6). A higher standard deviation indicates that the criterion has a greater ability to distinguish between different FSW experimental conditions.

The standard deviation is calculated using the equation(2)

$$\sigma_j = \sqrt{\frac{1}{m} \sum_{i=1}^m (r_{ij} - \bar{r}_j)^2} \quad (2)$$

where:

- r_{ij} = normalized value of the i^{th} experiment for criterion j
- $\bar{r}_j$ = mean value of criterion j
- m = number of experimental runs (8 in this research)

Table.6. Standard Deviation (σ_j) of each normalization values

Criterion	Standard deviation (σ_j)
UTS	0.3144
Impact Strength	0.3118
Hardness	0.3273

The calculated standard deviations indicate that hardness exhibits the highest contrast intensity (0.3273) among the evaluated mechanical properties, followed by UTS (0.3144) and impact strength (0.3118). This suggests that hardness provides the highest discriminatory information among the investigated FSW conditions.

5.1.3. Correlation coefficient matrix (ρ_{jk}) among UTS , Impact strength and Hardness

For the CRITIC weighting method, the correlation coefficient matrix (ρ_{jk}) is calculated to evaluate the relationship among the performance criteria. The correlation coefficient indicates the degree of similarity or conflict between the criteria.

The Pearson correlation coefficient is calculated by employing the equation(3)

$$\rho_{jk} = \frac{\sum_{i=1}^m (r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^m (r_{ij} - \bar{r}_j)^2} \sqrt{\sum_{i=1}^m (r_{ik} - \bar{r}_k)^2}} \quad (3)$$

where:

- r_{ij} and r_{ik} are normalized values of criteria j and k
- $\bar{r}_j$ and $\bar{r}_k$ are the mean normalized values
- m is the number of experimental runs

Using the normalized decision matrix of the eight AZ91D FSW experiments, the correlation coefficient matrix is obtained and furnished in Table.7.

Table.7. Correlation coefficient matrix (ρ_{jk}) among UTS ,impact strength and Hardness

Criteria	UTS	Impact strength	Hardness
UTS	1.0000	-0.4447	0.9541
Impact strength	-0.4447	1.0000	-0.4010
Hardness	0.9541	-0.4010	1.0000

5.1.4. CRITIC Conflict Matrix Component

For CRITIC analysis, the term $(1-\rho_{jk})$ represents the conflict intensity between criteria and furnished in Table.8.

Table.8. CRITC Conflict Matrix Component

Criteria Pair	Correlation (ρ_{jk})	Conflict Value ($1-\rho_{jk}$)
UTS–Impact Strength	-0.4447	1.4447
UTS–Hardness	0.9541	0.0459
Impact Strength–Hardness	-0.4010	1.4010

The results indicate that impact strength provides significant independent information because it has a negative correlation with both UTS and hardness. In contrast, UTS and hardness provide similar information due to their strong positive correlation.

5.1.5. Information content (C_j) and weights

Using the previously calculated standard deviations and correlation coefficient matrix, the information content (C_j) for each criterion in the CRITIC method by equation (4) and the magnitudes are furnished in Table.9. The criterion weights are computed by equation (5) and compiled in Table.10.

$$C_j = \sigma_j \sum_{k=1}^n (1 - \rho_{jk}) \quad (4)$$

$$w_j = \frac{c_j}{\sum c_j} \quad (5)$$

Table.9. Information content (C_j)

Criterion	σ_j	$\sum(1-\rho_{jk})$	C_j
UTS	0.3144	1.4906	0.4687
Impact strength	0.3118	2.8457	0.8874
Hardness	0.3273	1.4469	0.4735

Table.10. CRITIC Weight (w_j)

Criterion	CRITIC Weight (w_j)
UTS	0.256
Impact strength	0.486
Hardness	0.258

5.1.6. Normalized Decision Matrix for VIKOR method

The weighted normalized distance used in VIKOR is employed using equation (6) and the weighted results are furnished in Table.11.

$$d_{ij} = w_j \left(\frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right) \quad (6)$$

where;

w_j = CRITIC weight, f_j^* = best value, f_j^- = worst value.

Table.11. Normalized decision matrix

Run	UTS (N/mm ²)	Impact Strength(J)	Hardness (Hv)
1	0.0883	0.2430	0.0737
2	0.1266	0.1944	0.1290
3	0.2178	0.2916	0.2211
4	0.1207	0.2430	0.0921
5	0.2560	0.0000	0.2580
6	0.0000	0.4860	0.0000
7	0.1589	0.3888	0.1659
8	0.2472	0.0972	0.2396

5.1.7. Utility measure and Regret measures

The utility and regret measures as communicated by VIKOR method are computed by equation (7) and (8) respectively and from these VIKOR index values are computed by equation (9). (Table.12) is furnished with Utility, Regret and VIKOR index values by taking v as 0.5.

$$S_i = \sum_{j=1}^n w_j \left(\frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right) \quad (7)$$

$$R_i = \max_j \left[w_j \left(\frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right) \right] \quad (8)$$

$$Q_i = v \left(\frac{S_i - S^*}{S^- - S^*} \right) + (1 - v) \left(\frac{R_i - R^*}{R^- - R^*} \right) \quad (9)$$

Table.12. Utility and Regret measures Results

Run	S	R	Q
1	0.338	0.167	0.013
2	0.428	0.165	0.128
3	0.705	0.283	0.851
4	0.417	0.167	0.120
5	0.592	0.333	0.848
6	0.333	0.333	0.500
7	0.641	0.267	0.879
8	0.630	0.322	0.899

5.1.8 Analysis of Means and Analysis of Variance

The VIKOR index values (Q) are subjected to ANOM and ANOVA employing Taguchi technique using lower the better criterion. Figure.2. shows the ANOM plot while the Table.13. portrays the ANOVA computations along with the contribution of each parameter.

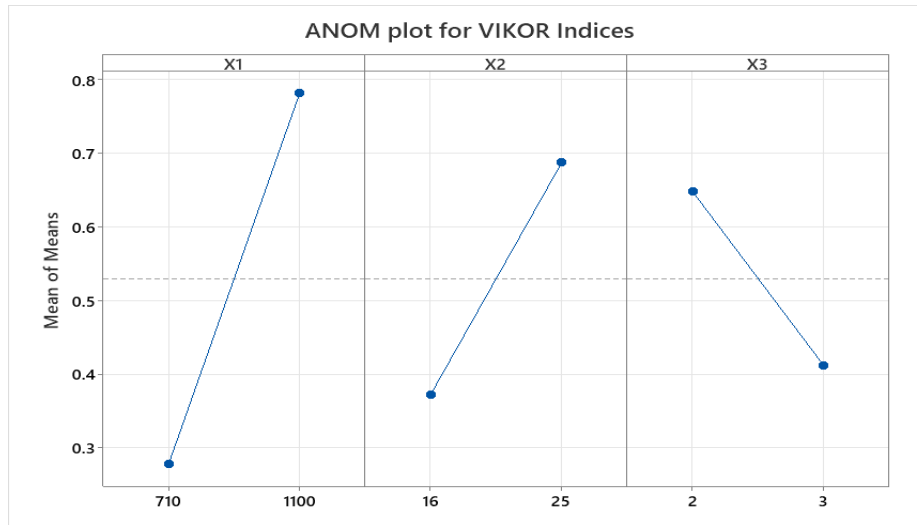


Figure.2. ANOM Plot

240

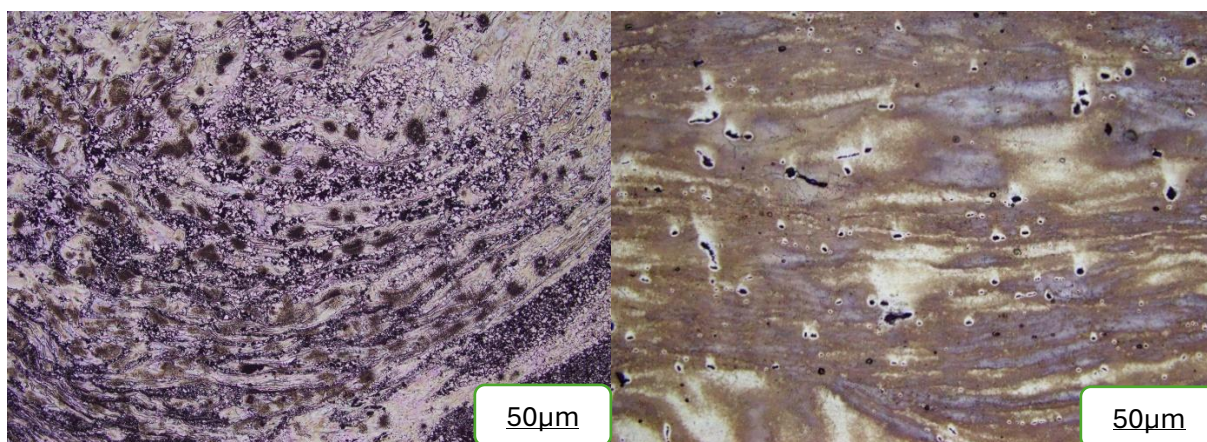
Table.13. ANOVA for VIKOR Indices

Source	DF	SS	MS	% Contribution
X1	1	0.507	0.50702	47.83
X2	1	0.1985	0.19845	18.73
X3	1	0.1114	0.11139	10.51
Error	4	0.2432	0.06079	
Total	7	1.06		

241

242 6.0.Discussion

243 It is difficult to deform Magnesium alloy at room temperature due to insufficient number of slip systems. Hence the
 244 heating is provided by rotating tool in the FSW process. The strength has increased at low speeds while at high speeds
 245 excessive heat generated and grain coarsening occurred and consequently strength is reduced. Highest impact
 246 toughness has occurred at 1100 rpm in Run 5 due to grain coarsening formed with the high heat inputs. The grains are
 247 fine at weld centre due to dynamic recrystallization and they block dislocation movement and enhances hardness. It
 248 is observed clearly at high speed and low feed rate causes grain coarsening due to high input (Run 6). Tensile strength
 249 and hardness at weld centre are high while the impact toughness is low in Run 6 in consonance with the results of
 250 other non ferrous materials [5].



251

(a) TMAZ**(b) Welded Zone**

252

253

Figure.3. Microstructure of welded zones

Figure.3.a. Optical micrograph of the TMAZ zone friction stir welded AZ91D magnesium alloy showing a dynamically recrystallized α -Mg matrix with uniformly distributed fragmented β -Mg₁₇Al₁₂ intermetallic particles. The characteristic material flow bands indicate intense plastic deformation and efficient material mixing during the friction stir welding process. Figure.3.b. illustrates the optical microstructure of the welded zone of friction stir welded AZ91D magnesium alloy reinforced with cerium powder at the joint interface under 200X magnification. The stir zone exhibits a dynamically recrystallized Mg matrix with uniformly distributed fine second-phase particles. The original coarse Mg₁₇Al₁₂ eutectic network has been significantly fragmented and redistributed owing to severe plastic deformation during friction stir welding. The addition of cerium promotes grain refinement and suppresses the coarsening of intermetallic phases by forming thermally stable Ce-containing compounds. Characteristic material flow bands confirm efficient stirring and homogeneous particle distribution within the weld nugget. The refined microstructure and homogeneous dispersion of reinforcement particles are expected to improve the mechanical performance and microhardness of the welded joint compared with conventional friction stir welded AZ91D alloy.

Figure.4. shows the SEM micrograph of the stir zone of friction stir welded AZ91D magnesium alloy reinforced with cerium powder at the joint interface. The microstructure consists of a dynamically recrystallized Mg matrix containing a homogeneous dispersion of fine second-phase particles. The severe plastic deformation imposed during friction stir welding fragmented the original coarse Mg₁₇Al₁₂ eutectic network into finely dispersed particles. The addition of cerium promoted further refinement by forming thermally stable Ce-containing intermetallic compounds and restricting grain growth during recrystallization through particle pinning.[19-20]

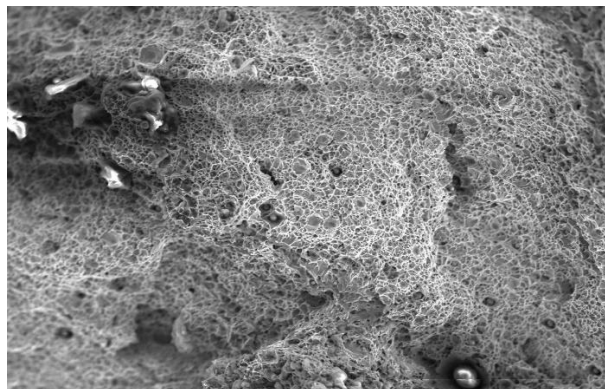


Figure.4.SEM Micrograph at stir zone of Tensile tested specimen

The optimal parameter condition is retrieved from the ANOM plot (Figure.2) and is found to be at low level for the parameters tool rotational speed and weld speed while tool tilt angle must be at higher level. The condition is matching with the Run2 of the experiment design.

The contribution parameter to the overall variance in mechanical properties is evaluated; the tool rotational speed contributes to the largest extent of 47.83% while weld speed is to the tune of 18.73% in achieving the overall comprehensive mechanical property achievement in the current FSW joining process.

A confirmation experiment was carried out at the optimal parameter condition found by Taguchi method and the result is presented in Table.14.

Table.14. Results of Confirmation Experiments

Rotational Speed(X1)	Weld Speed(X2)	Tool Tilt Angle (X3)	UTS (MPa)	Impact Toughness(J)	Hardness (Hv)
710	16	3	103	1.63	69.5

7.0 Conclusions

- ❖ The critic weighting has been evaluated based on variability and degree of conflict done away the subjectable approaches.
- ❖ The highest CRITIC weight was attributed to Impact toughness while UTS was done with the least.
- ❖ The VIKOR index has been evaluated by considering group utility and individual regret value. Thus most ideal solutions was brought in the multi response decision process.
- ❖ The individual parameter contribution and the level at which the optimal condition can be achieved has been evaluated by Taguchi method.
- ❖ The tool rotational speed has played for highest contribution of 47.83%. The speed thus generated the heat and consequently affected the grain coarsening; the refinement of grains have occurred due to dynamic recrystallization process.
- ❖ Addition of cerium at the interface restricted the grain growth during recrystallization through particle pinning.

297 **Declaration:**

298 Ethics approval and consent to participate:

299 This work was done as per the conceptualisation of our ideas and not copied from anywhere. Hence ethics
300 approval is irrelevant for us.

301 **Consent for publication:**

302 We are agreeing for publication of this current article in your esteemed journal.

303 **Availability of data and material:**

304 The material and data are available and included in the paper. It will be with us and shall be submitted upon
305 request.

306 **Competing interests:**

307 The authors declare no competing interests.

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310 **Authors' contributions:**

311 Dr. Vaddi Venkata Satyanarayana : Conceptualization, Methodology & supervision Writing-review & editing
312 with analysis.

313 Dr. Kesavapatnam Rajesh Kumar: Data curation, Investigation, Writing-Original draft and formal analysis.

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