

MACHINE LEARNING-ASSISTED PREDICTION AND VIKOR-BASED OPTIMIZATION OF MECHANICAL PROPERTIES IN MICRO- FRICTION STIR WELDED MONEL 400 SHEETS

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Received 11.03.2026.
Revised 01.06.2026.
Accepted 10.07.2026.

Keywords:

Micro-friction stir welding,
Monel 400, machine learning,
VIKOR, tensile properties,
micro-hardness, surface
roughness

ABSTRACT

Micro-friction stir welding (μ -FSW) of 0.6 mm Monel 400 sheets was investigated for butt and lap configurations using a tungsten-carbide tool. Four experimentally produced weld profiles were evaluated for tensile properties, micro-hardness, surface roughness and weld-nugget microstructure. Machine-learning models were used as exploratory tools to study relationships between process variables and measured responses; experimental observations and synthetic augmented records are explicitly distinguished in the revised methodology. Synthetic records are not treated as independent experiments and are not used as the basis for the VIKOR decision matrix. The experimental decision matrix was analysed using the VIKOR compromise-ranking procedure with equal criterion weights. Using ultimate tensile strength, yield strength, elongation and hardness as benefit criteria and surface roughness as a cost criterion, profile L2 ranked first ($Q = 0.000$), followed by L1, B2 and B1. A $\pm 20\%$ one-at-a-time weight perturbation around equal weighting retained the same ranking. The study therefore identifies L2 (800 rpm, 20 mm/min, 5.5 kN) as the best compromise among the four tested conditions while clearly limiting conclusions to the available experimental dataset.



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1. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process that uses a non-consumable rotating tool to generate frictional heating and plasticised material flow. It has been applied to aluminium, magnesium, copper and nickel-based materials because the process can avoid several defects associated with conventional fusion welding. However, studies on ultra-thin Monel 400, particularly direct comparisons of butt and lap micro-

FSW configurations, remain limited. Micro-friction stir welding of sub-millimetre sheets has been studied in both butt and lap configurations, including thin aluminium systems (Ahmed et al., 2015; Huang et al., 2017; Zhang et al., 2019).

Monel 400 is a nickel-copper alloy used where strength and corrosion resistance are important, including marine, chemical and process-industry applications. The present work investigates 0.6 mm Monel 400 sheets welded

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under four distinct parameter combinations. The measured responses are tensile strength, yield strength, elongation, micro-hardness and surface roughness, together with optical observations of the weld nugget zone (WNZ). Previous studies on Monel 400 and related nickel-based alloys have examined joint formation, heat input, microstructure and mechanical response (Aghaei & Dehghani, 2015; Heidarzadeh et al., 2019; Lemos et al., 2017; Song et al., 2013). Related thin-sheet studies also show that tool configuration and process parameters can influence mechanical properties and microstructure (Forcellese et al., 2012; Simoncini & Forcellese, 2012), while thin Monel 400 foil has also been joined using pulsed Nd:YAG laser welding (Ventrella et al., 2011).

The revised manuscript separates three roles that were previously mixed: (i) experimentally measured observations, which support the physical conclusions; (ii) synthetic records used only for exploratory ML augmentation; and (iii) VIKOR ranking, which is based only on representative experimental property values. This distinction is essential because synthetic observations are not independent experiments and cannot replace experimental validation.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and welding tool

Ultra-thin Monel 400 sheets with dimensions of 150 mm × 60 mm × 0.6 mm were used. The nominal chemical composition supplied for the material is given in Table 1. A straight cylindrical tungsten-carbide (WC) tool was used for μ -FSW because of the strength and thermal resistance required for welding the nickel–copper alloy. The fabricated WC tool and the holding fixture are shown in Figure 1 and Figure 2, respectively.

Table 1. Chemical composition of Monel 400

Element	Percentage composition
Carbon	0.3 max
Silicon	0.5 max
Manganese	2.0 max
Sulphur	0.024 max
Iron	2.5 max
Copper	28.0–34.0
Nickel (plus cobalt)	63.0 min



Figure 1. Fabricated WC tool



Figure 2. Fabricated fixture for holding Monel sheets

2.2 Welding operation and tested parameter combinations

The sheets were clamped to the backing plates of the fixture and welded on a linear friction stir welding machine. Butt profiles were coded μ FSW–B1 and μ FSW–B2, and lap profiles were coded μ FSW–L1 and μ FSW–L2. The four experimentally tested combinations are listed in Table 2. No additional process conditions are introduced in this revision. The welding-machine arrangement used for the experiments is shown in Figure 3. Related friction-stir lap welding studies have likewise demonstrated that process parameters can substantially affect joint response (Tan et al., 2017).

Table 2. Experimentally tested μ -FSW process conditions

Profile	Tool rotational speed (rpm)	Tool travel speed (mm/min)	Axial load (kN)
μ FSW–B1	600	15	5.0
μ FSW–B2	700	20	4.5
μ FSW–L1	700	15	6.0
μ FSW–L2	800	20	5.5



Figure 3. Friction stir welding machine setup

2.3 Specimen preparation and measurement procedures

Tensile specimens were machined from the welded sheets using wire-cut EDM according to the ASTM E8M-based specimen procedure used in the experimental work. The original study records a 25 mm gauge length and a crosshead/loading rate of 1 mm/min. The present revision does not claim additional compliance details that are not available in the experimental records. Micro-hardness was measured using a Vickers indenter with 100 g load and 10 s dwell, following the ASTM E384 procedure stated in the study. Surface roughness parameters were measured using a profilometer following ISO 4287 as stated in the experimental record, with a 1.25 mm evaluation length. Optical microscopy was performed at 50× magnification after polishing and etching with 5% picral. The tensile-specimen preparation is illustrated in Figure 4 and the wire-cut EDM specimens are shown in Figure 5.

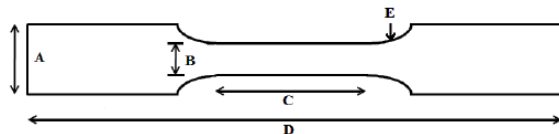


Figure 4. Weld specimens machined for butt and lap configurations

The tensile and hardness procedures are referenced to ASTM E8/E8M and ASTM E384, respectively (ASTM International, 2022, 2025), while the surface-texture terminology follows ISO 4287:1997 as stated in the

experimental record (International Organization for Standardization, 1997).

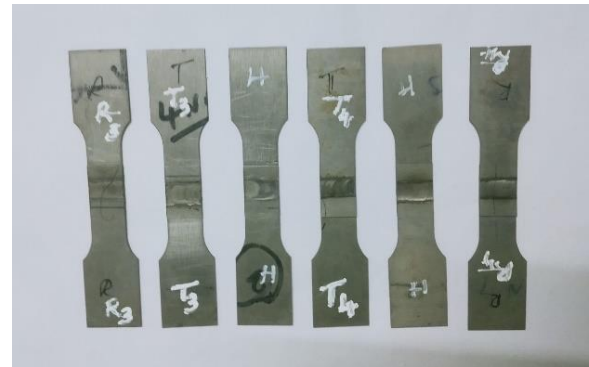


Figure 5. Specimens prepared from wire-cut EDM

2.4 Data provenance, synthetic augmentation and ML validation protocol

The central revision to the methodology is explicit data provenance. The four weld profiles are the independent experimental alternatives used for physical comparison and VIKOR ranking. The original ML workflow also generated synthetic augmented records by perturbing measured inputs/response profiles. Those records are retained only as computational augmentation for exploratory model fitting and trend visualisation; they are not described as new experiments, are not used as independent experimental validation, and are not used to populate the VIKOR decision matrix. The permitted use of each dataset component is summarized in Table 3.

Table 3. Data provenance and permitted use in the revised analysis

Dataset component	Source	Permitted use	Not used for
Tensile properties	Measured B1, B2, L1 and L2 profiles	Experimental comparison; VIKOR inputs	Independent ML test-set claim
Micro-hardness profile	Measured hardness observations across the weld zone	Experimental hardness discussion; exploratory spatial modelling	Independent profile-level generalisation claim
Surface roughness	Measured B1, B2, L1 and L2 profiles	Experimental comparison; VIKOR inputs	Independent ML test-set claim
Synthetic/augmented records	Computational perturbation of measured data described in the original workflow	Exploratory training and trend visualisation only	Experimental conclusions, VIKOR inputs, independent validation

For any future re-analysis of the same ML workflow, preprocessing and augmentation must be performed inside each training fold only: encoders/scalers are fitted on training data, synthetic records are generated only from training observations, and no synthetic relative of a test observation may enter training. Because the present profile-level tensile and roughness dataset contains only four independent weld conditions, statistically strong k-fold performance estimates, confidence intervals and independent experimental validation cannot be created honestly from the supplied data. Accordingly, the revised manuscript does not present the augmented-data R^2 /MAE values as independent experimental predictive accuracy. This is a limitation of the available dataset, not a change to the measured experimental values.

3. VIKOR MULTI-CRITERIA OPTIMIZATION

VIKOR was applied to rank the four experimentally tested alternatives. Ultimate tensile strength (UTS), yield strength (YS), elongation and Vickers hardness (HV) were treated as benefit criteria to be maximized. Surface roughness R_a was treated as a cost criterion to be minimized. Equal weights were used because no experimentally supported basis for preferential weighting was available: $w_j = 0.20$ for each of the five criteria. The compromise parameter was $v = 0.50$. The VIKOR framework follows the compromise-ranking approach described by Opricovic and Tzeng (2007).

3.1 Experimental decision matrix

The experimental decision matrix used for the VIKOR analysis is presented in Table 4.

Table 4. Experimental decision matrix used for VIKOR

Alternative	UTS (kgf/mm ²)	YS (kgf/mm ²)	Elongation (%)	HV	Ra (μm)
B1	387.0	217.0	7.5	266	0.670
B2	404.0	242.0	7.0	293	0.551
L1	556.0	256.0	28.5	345	0.857
L2	559.0	263.0	26.5	296	0.413

3.2 Normalization and S, R and Q calculations

For a benefit criterion, the normalized distance from the best value was calculated as $d_{ij} = (f_{ij}^* - f_{ij}) / (f_{ij}^* - f_{-j})$. For the cost criterion, $d_{ij} = (f_{ij} - f_{ij}^*) / (f_{-j} - f_{ij}^*)$, where f_{ij}^* is the best value and f_{-j} is the worst value for criterion j . The group utility and individual regret were calculated as $S_i = \sum w_j d_{ij}$ and $R_i = \max_j(w_j d_{ij})$. The VIKOR index was then $Q_i = v(S_i - S^*) / (S - S^*) + (1-v)(R_i - R^*) / (R - R^*)$, with $v = 0.50$. Lower S , R and Q values indicate closer compromise performance. The resulting normalized distances are reported in Table 5.

Table 5. Normalized VIKOR distances (0 = best, 1 = worst)

Profile	UTS	YS	Elongation	HV	Ra
B1	1.000	1.000	0.977	1.000	0.579
B2	0.901	0.457	1.000	0.658	0.311
L1	0.017	0.152	0.000	0.000	1.000
L2	0.000	0.000	0.093	0.620	0.000

Table 6. VIKOR results and compromise ranking

Profile	S	R	Q	Rank
L2	0.143	0.124	0.000	1
L1	0.234	0.200	0.559	2
B2	0.665	0.200	0.840	3
B1	0.911	0.200	1.000	4

The standard VIKOR calculations reproduce the ranking $L2 > L1 > B2 > B1$. $L2$ has the lowest S and R values and therefore $Q = 0.000$ under the equal-weight, $v = 0.50$ compromise setting. The VIKOR results and final compromise ranking are reported in Table 6.

3.3 Weight-sensitivity analysis

A one-at-a-time $\pm 20\%$ relative perturbation was applied to each equal criterion weight: the selected criterion was set to 0.16 and 0.24, while the remaining four criteria shared the residual weight equally. This sensitivity analysis uses the same experimental decision matrix and introduces no new measurements. In all ten perturbation cases, the ranking remained $L2 > L1 > B2 > B1$, indicating that the reported first-ranked alternative is stable to moderate weight variation around the equal-weight assumption. The sensitivity results are

summarized in Table 7. The VIKOR Q -index ranking of the four experimental weld profiles is shown in Figure 6.

Table 7. VIKOR sensitivity summary for $\pm 20\%$ relative perturbation of one criterion weight

Perturbed criterion	Weight range tested	Ranking retained
UTS	0.16–0.24	$L2 > L1 > B2 > B1$
YS	0.16–0.24	$L2 > L1 > B2 > B1$
Elongation	0.16–0.24	$L2 > L1 > B2 > B1$
HV	0.16–0.24	$L2 > L1 > B2 > B1$
Ra	0.16–0.24	$L2 > L1 > B2 > B1$

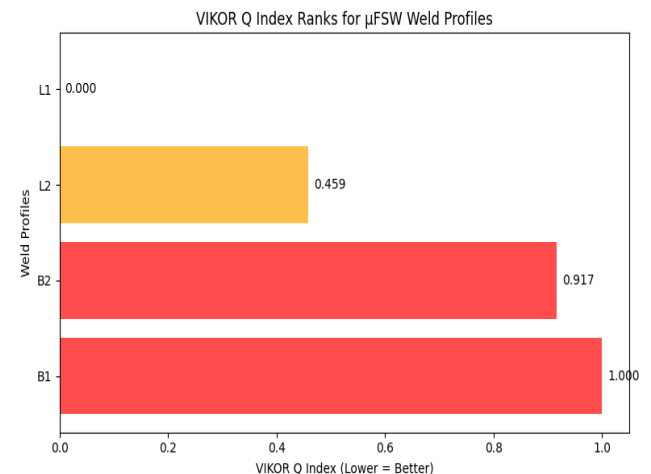


Figure 6. VIKOR Q -index ranking of the four experimental weld profiles

4. RESULTS AND DISCUSSION

4.1 Tensile properties

The experimentally measured tensile properties are summarized in Table 8. The lap profiles produced substantially higher UTS and YS than the butt profiles. $L2$ produced the highest UTS (559 kgf/mm²) and YS (263 kgf/mm²), while $L1$ produced the highest elongation (28.5%). Within the tested conditions, the results therefore show a clear difference between the two joint configurations; however, the present four-condition dataset should not be used to claim a universal monotonic process-parameter law.

Table 8. Experimental tensile properties of butt and lap welded joints

Profile	Tool speed (rpm)	Travel speed (mm/min)	UTS (kgf/mm ²)	YS (kgf/mm ²)	Elongation (%)
B1	600	15	387	217	7.5
B2	700	20	404	242	7.0
L1	700	15	556	256	28.5
L2	800	20	559	263	26.5

The observed superiority of the lap profiles is discussed in relation to material flow and the weld-nugget microstructure visible in the optical micrographs. The available measurements support comparison of the tested profiles but do not provide replicate statistics; therefore, standard deviations and confidence intervals are not reported because they cannot be calculated from the supplied profile-level values without adding or inventing replicate data. Related work on nickel-based friction-stir-welded alloys has also linked process conditions with microstructural and mechanical changes (Lemos et al., 2019; Song & Nakata, 2010).

4.2 Micro-hardness

Micro-hardness was measured across the weld zone from –6 mm to +6 mm. The reported peak hardness was 345 HV for L1, 296 HV for L2 and 266 HV for B1. The hardness profiles show a pronounced change across the WNZ and lower values toward the outer regions. These spatial measurements provide the richest experimental response set in the study, but they remain observations from the four reported weld conditions rather than independent additional weld trials. The experimental micro-hardness profiles associated with the original Bagging and Random Forest comparisons are shown in Figure 7 and Figure 8, respectively.

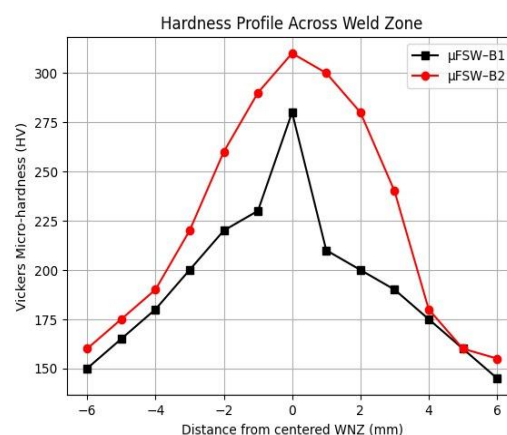


Figure 7. Experimental micro-hardness profile used for the original Bagging comparison

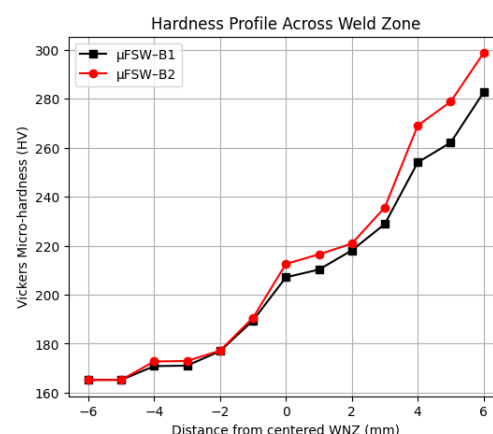


Figure 8. Experimental micro-hardness profile used for the original Random Forest comparison

4.3 Surface roughness

The surface roughness results are given in Table 9. L2 produced the lowest Ra value (0.413 μm), followed by B2 (0.551 μm), B1 (0.670 μm) and L1 (0.857 μm).

Because Ra is a cost criterion in VIKOR, the low roughness of L2 strongly contributes to its compromise ranking. The exploratory Random Forest and Bagging trend comparisons for surface roughness are shown in Figure 9 and Figure 10, respectively.

Table 9. Experimental surface roughness parameters

Profile	RPM	Travel speed (mm/min)	Ra (μm)	Rq (μm)	Rz (μm)
B1	600	15	0.670	0.850	4.2
B2	700	20	0.551	0.720	3.5
L1	700	15	0.857	1.05	5.1
L2	800	20	0.413	0.520	2.8

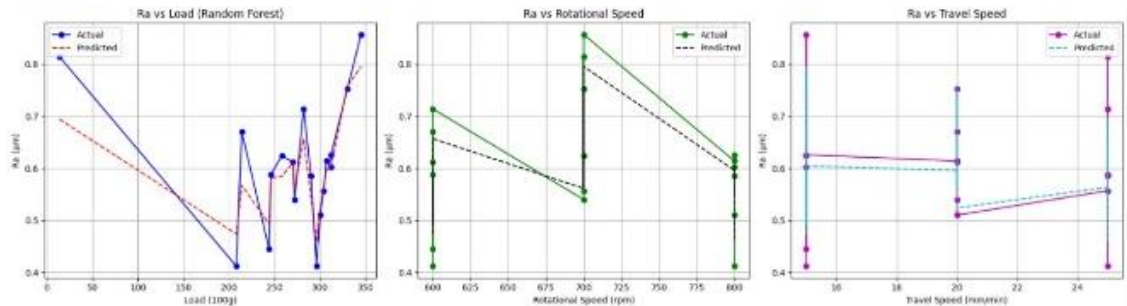


Figure 9. Random Forest trend comparison for surface roughness (exploratory augmented-data analysis)

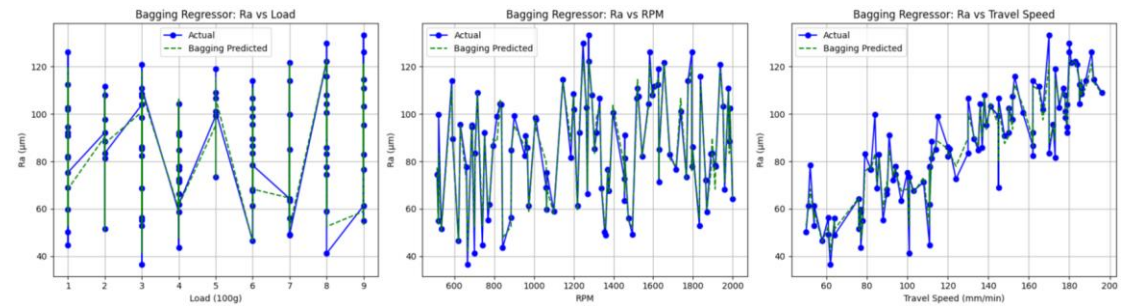


Figure 10. Bagging trend comparison for surface roughness (exploratory augmented-data analysis)

4.4 Microstructure

Optical micrographs of the WNZ were obtained at 50 $\times$ magnification and 500 μm resolution for the four profiles. The images are used here as qualitative support for the observed differences among the tested welds. No numerical grain-size dataset is added in this revision; consequently, quantitative grain-size claims are avoided. The weld-nugget-zone (WNZ) micrographs for μFSW –B1, μFSW –B2, μFSW –L1 and μFSW –L2 are presented in Figures 11–14, respectively.

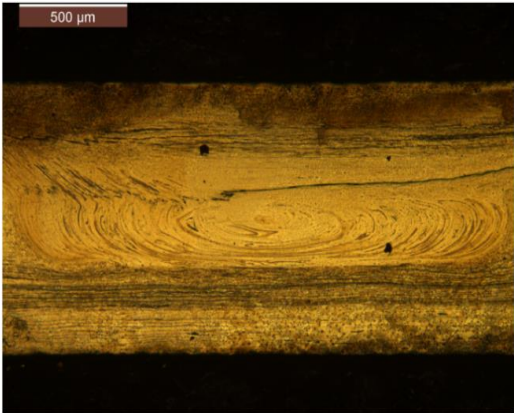


Figure 11. WNZ for μFSW –B1 (600 rpm)

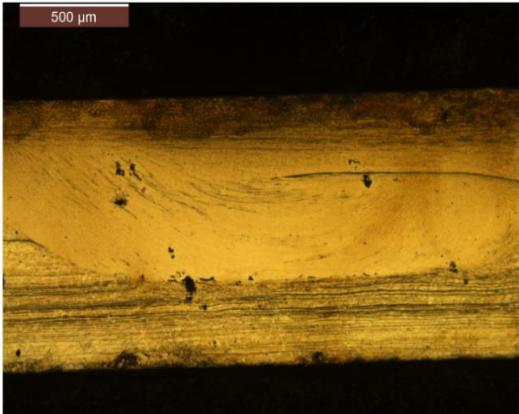


Figure 12. WNZ for μFSW –B2 (700 rpm)

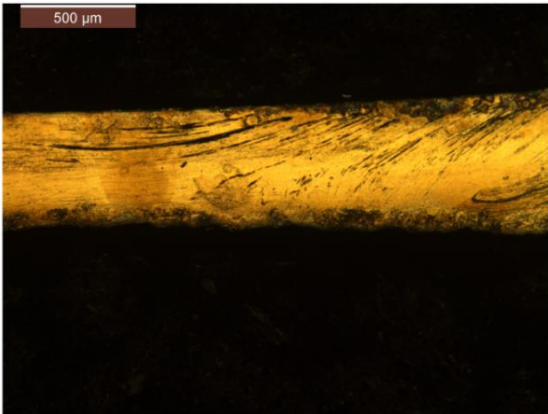


Figure 13. WNZ for μFSW –L1 (700 rpm)

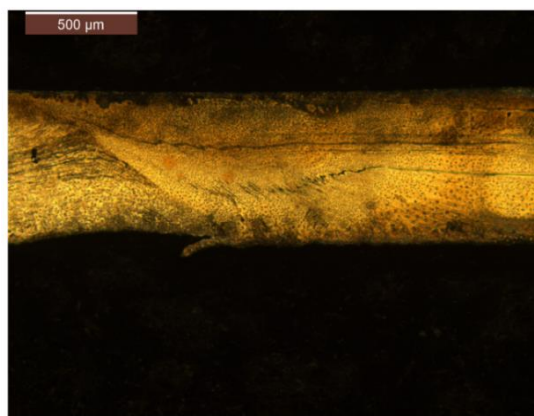


Figure 14. WNZ for μ FSW–L2 (800 rpm)

4.5 Interpretation of the machine-learning results

The original manuscript reported Random Forest and Bagging results after synthetic augmentation. Those computations may be useful for exploratory interpolation and visualisation, but their very high R^2 values can be optimistic when synthetic records are closely derived from the same measured observations. In the revised interpretation, the ML outputs are therefore treated as supportive trend models rather than independently validated predictors.

The principal evidence for the paper's engineering conclusions is the measured dataset: L2 has the highest measured UTS and YS and the lowest Ra, L1 has the highest measured elongation and hardness, and VIKOR provides an explicit compromise calculation across these conflicting responses. The ML component is retained as an exploratory computational layer, with the limitation that an independent experimental validation set is not available in the present data. Future validation should use additional independently welded conditions and report fold-wise or independent-test R^2 , MAE, RMSE, bias and confidence intervals without mixing synthetic relatives across train/test partitions.

5. CONCLUSION

Micro-friction stir welding of 0.6 mm Monel 400 sheets was evaluated for two butt and two lap configurations. The conclusions are restricted to the four experimentally

tested conditions and the measured data supplied in this study.

- 1) The lap profiles produced higher measured tensile properties than the butt profiles. L2 recorded the highest UTS (559 kgf/mm²) and YS (263 kgf/mm²), while L1 recorded the highest elongation (28.5%).
- 2) The peak reported hardness was 345 HV for L1, whereas L2 produced 296 HV. L2 also produced the lowest measured Ra value of 0.413 μ m.
- 3) The VIKOR analysis was strengthened by explicitly reporting the experimental decision matrix, benefit/cost normalization, equal weights, S, R and Q calculations. The ranking was $L2 > L1 > B2 > B1$, with L2 giving $Q = 0.000$ under $v = 0.50$.
- 4) A $\pm 20\%$ one-at-a-time perturbation around equal criterion weights retained the same ranking, supporting the stability of L2 as the best compromise under moderate weight variation.
- 5) Experimental and synthetic records are explicitly separated. Synthetic augmentation is not treated as experimental evidence and is not used for VIKOR ranking. Because only four independent profile-level tensile and roughness conditions are available, independent experimental validation, profile-level k-fold confidence intervals and replicate variability statistics cannot be claimed from the present dataset. The ML results are therefore positioned as exploratory rather than independently validated general-purpose predictors.

Acknowledgement: The authors acknowledge the Department of Manufacturing Engineering, Annamalai University, Microlab Chennai and Prasanna Precision Tools, Puducherry.

Author Contributions: Srujan Manohar MVN: conceptualization, methodology and investigation. Mahadevan K and Arun P: original draft preparation. Varsala Pragna and Mallikarjunachari G: review and editing. All authors reviewed the manuscript.

Funding: This research received no external funding and was self-funded by the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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