Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 8s (2025)

Machine Learning Approach for Optimal Parameter Estimation in Vibratory Welding

Dr Rashmi Dwivedi [1], K . Ch Sekhar [1*,2], Dr. V.V. Rama Reddy[2]

[1,] Department of Mechanical Engineering, School of Engineering, Sri Satya Sai University of Technology & Medical Sciences, Sehore, M.P., India.

[2] Department of Mechanical Engineering, Lendi Institute of Engineering and Technology , Vizianagaram, Andhra Pradesh, India.

*Corresponding Author: sekhar.lendi@gmail.com

Article History:

***Received:** 26-10-2024*

***Revised:**25-11-2024*

***Accepted:**27-12-2024*

Abstract:

Vibratory treatment during welding process is proved to reduce residual stresses in the weld joint and improve mechanical properties. But optimal setting of vibration parameters such as frequency, amplitude and time is essential to obtain maximum improvement strength of the joint. Identification of such optimal parameter set through series of experimentation is very critical due to severe consumption of resources. The research is aimed to identify optimal setting of parameters through machine learning approach for the welding of SS304 in the gas metal arc welding (GMAW) process. Supervised learning is preferred to run in the convolution neural networks (CNN) by feeding the algorithm with essential data about the mechanical properties. The response is observed for varying the frequency of workpiece, electrode at different voltages as the time kept constant and amplitude found with adverse-affect over weld strength. The observed readings are tested through experimental investigation and confirmed the response in mechanical properties such as tensile strength and hardness are obtained within the acceptable range of deviation. Microstructural characterization is performed to record the evidence over the grain refinement to support the maximum enhancement in mechanical properties of weld joint.

Keywords: machine learning, gas metal arc welding, convolutional neural networks, vibratory welding, tensile strength

Abbreviations:

GMAW - gas metal arc welding

CNN - convolution neural networks

ML - Machine learning

SEM - scanning electron microscopy

RFR - Random Forest Regression

1. Introduction:

Global demand to produce sophisticated products and high-end equipment brought various advancements, upgradations in the manufacturing sector. Vibratory treatment is one of such improvements which applied on the welding process to improve the strength of the joint by removing residual stresses [1]. It is proven that the vibratory treatment can provide effective channel to evacuate excessive heat and air traps which usually deteriorates the weld strength. But, proper setting of various welding parameters such as amplitude, frequency and time to achieve maximum enhancement in the mechanical properties of the welded joint [2]. Machine learning (ML) is most effective artificial intelligence method which used to solve multi-objective optimization problems in different manufacturing operations [3].

Balachandar and Jagadeesh Aran et al. applied machine learning approach for improving the welding strength in the friction stir welding to the various commercial applications and stated that the random forest given best weld parameter set compared to other ML algorithms namely hoeffeding, logistic model tree, decision tree [4]. Mongan et al. applied hybrid ML approach to predict the quality of the lap joint produced between Al5754 plates through the ultrasonic metal welding process. It is observed that the error of prediction is reduced from 13.17 to 7.51% than the other statistical techniques and observed that the surface cracks is forming due to excess amount of plastic strain with the excessive clamping pressure [5]. Vidal et al. performed regression analysis through ML approach and attained the microhardness with the accuracy of + 3% in the laser welding of A36 steel sheets. It is observed that the amplitude of 0.56mm and frequency of workpiece at 1034 Hz can bring the maximum enhancement in the hardness of the weld joint [6]. Das et al. applied various ML algorithms such as random forest, reduced error pruning tree, support vector regression, multi-layer perceptron etc. to estimate the residual stresses formation in the SS304 during electron beam welding through vibratory treatment and the obtained results are validated through the X-ray diffraction technique (XRD) [7]. Schwarz et al. developed central composite design to make design of experiments and applied ML algorithm to monitor process improvement of Cu-sheet welds through ultrasonic metal welding process [8]. Jang et al. applied ML algorithm to detect weld porosity at different frequencies in the vibratory treatment assisted gas tungsten arc welding process and studied X-ray images to validated the obtained results [9]. Sapthapathy et al. applied artificial neural networks in the ML approach to study the weld strength of Cu sheets through ultrasonic metal welding process and observed that the applied model results with 1% error [10].

Sabzi and Dezfuli studied the influence of vibratory treatment over the microstructure and mechanical properties over the 316L stainless steel joints developed by using gas-tungsten arc welding and observed the columnar type dendrites exhibited lower length than the equiaxed dendrites which contributed to exhibit higher mechanical properties than the non-vibratory assistance [11]. Singh et al. applied Taguchi analysis for optimizing process parameters in the vibratory welding to achieve maximum enhancement in the hardness of the butt joint and performed microstructural analysis to study the grain refinement in weldments. It is observed that the auxiliary vibrations supplied to weld zone prompted to significant refinement in the grain structure and leads to improvement in the studied mechanical property [12]. Wang et al. applied flux cored arc welding supported with vibratory treatment and studied the influence over microstructure of the weldments. It is observed that proeutectoid ferrite occupied more than the ferrite side, acicular ferrite in the weld zone and observed the effective integrated balance achieved between the yield strength, toughness of the metal [13]. Liu et al. investigated the mechanical properties of the butt joint established between the 2024 Al-T4 through friction stir welding under the assistance of vibratory treatment and observed the greater improvement in the tensile strength compared to yield, hardness of the weldments [14]. Yuvaraj et al.

applied cold metal transfer welding for the development of butt joint for similar metal welding of AISI304 stainless steel under vibratory treatment and observed the greater refinement in the fusion region at amplitude of 99 µm and welding currents of 95A [15].

The research is focused to address the above stated gaps in the vibratory welding and obtain optimal parameter set from the frequency of workpiece, electrode at different voltages through GMAW of SS304. Section-2 describes the application of ML approach over the designed multi-objective optimization problem and working of CNN algorithm on producing the pareto-optimal set. Section-3 presents the results obtained about the various mechanical properties and discussions over the enhancement or decrements in the studying properties at different frequencies. Section-4 presents the microstructural characterization made on the weld joint through scanning electron microscopy (SEM) for studying grain refinement with the introduction of vibratory treatment in the weld joint. Section-5 concludes the article by stating overall idea and major identifications in the performed multi-objective optimization problem through applied technique.

2. Application of ML:

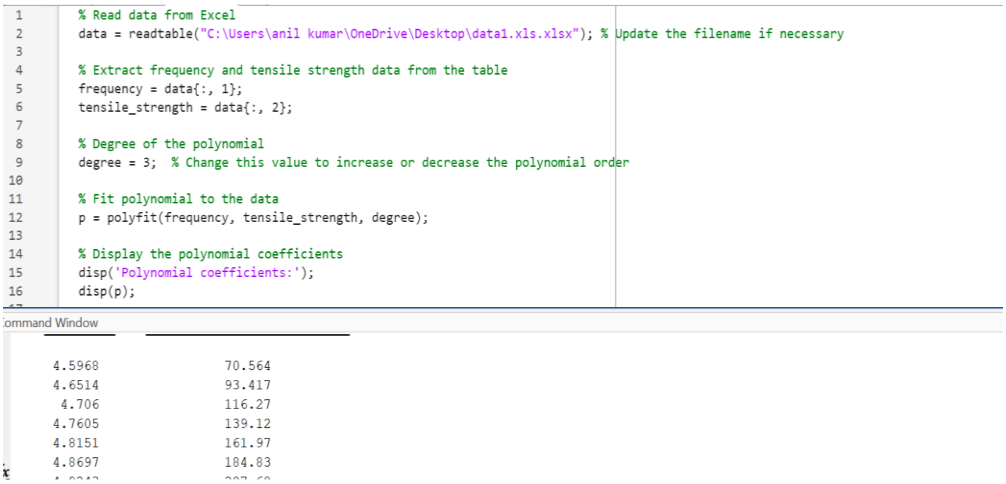
Gas metal arc welding (GMAW) with the assistance of vibratory treatment is preferred to join the similar metals such as SS304 through a butt joint. The parameters such as amplitude, time and frequency are most influenced in the vibratory treatment process and voltage supplied during the welding process can influence the strength of the butt joint before the weldment. Although the identified parameters can play significant role in the weld strength improvement, the manipulation of most influential parameter is essential for obtaining maximum enhancement in the studying mechanical properties. Random Forest Regression (RFR) is applied to test the dependency of influencing parameter and obtained as the frequency; voltage have greater influence over the alteration in the mechanical properties of the weld joint. The parameters such as frequency of work piece, electrode and voltage of the motor is taken into consideration for the present study whereas the amplitude, time is taken at constant. The upper and lower limits were chosen to avoid the deposition of filler metals at the bottom, the occurrence of heavier porosities, and splash during the GMAW [16]. The experiments were designed with three factors at five different levels based on the parameters chosen to study their influence over the properties such as tensile strength and hardness. The designed levels and chosen parameters for the vibratory treatment assisted GMAW process are enlisted in Table 1.

Table 1 Levels and Parameters.

Parameters	**Levels**				
	-2	**-1**	**0**	**1**	**2**
Workpiece frequency (Hz)	2	4	6	8	10
Electrode frequency (Hz)	200	400	600	800	1000
Motor Voltage (V)	2	4	6	8	10

Fig. 1 represents the code used to supply in the machine learning algorithm through MATLAB.

ISSN: 1074-133X
Vol 32 No. 8s (2025)


```
% Read data from Excel
data = readtable("C:\Users\anil kumar\OneDrive\Desktop\data1.xls.xlsx"); % Update the filename if necessary

% Extract frequency and tensile strength data from the table
frequency = data{:, 1};
tensile_strength = data{:, 2};

% Degree of the polynomial
degree = 3;  % Change this value to increase or decrease the polynomial order

% Fit polynomial to the data
p = polyfit(frequency, tensile_strength, degree);

% Display the polynomial coefficients
disp('Polynomial coefficients:');
disp(p);
```

```
Command Window

    4.5968          70.564
    4.6514          93.417
     4.706          116.27
    4.7605          139.12
    4.8151          161.97
    4.8697          184.83
```

Fig. 1. Run of Machine learning algorithm in MATLAB

The user-defined parameters are chosen based on training the values of the Correlation Coefficient (CC). The user-defined parameter value that has the maximum CC for the training data set is chosen for predicting the mechanical properties such as tensile and hardness of the butt joint.

3. Results and Discussions:

After supplying the essential details to the API, the algorithm examines the supplied data and understands the features. The variables are examined under the algorithm and produces the results from the supplied data.

3.1. Tensile strength:

The response of tensile strength for the butt joint can be made through GMAW process is tested at different ranges of frequency by varying electrode and workpiece individually at different voltages. It is given that the data is supplied for different frequences of the electrode and workpiece possible improvement in the tensile strength of the weld joint is displayed by the algorithm. The obtained responses are plotted and represented in the fig. 2. The test is performed on Universal Testing Machine (UTM) to validate the tensile strength of the vibratory welded specimens at highest possible enhancement and respective decrement with the further manipulation of the frequencies about workpiece and electrode.

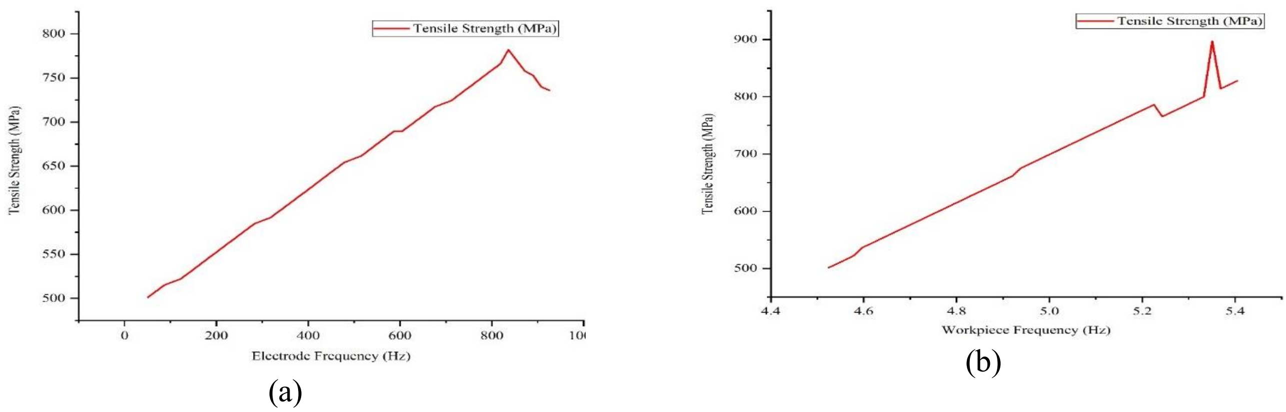
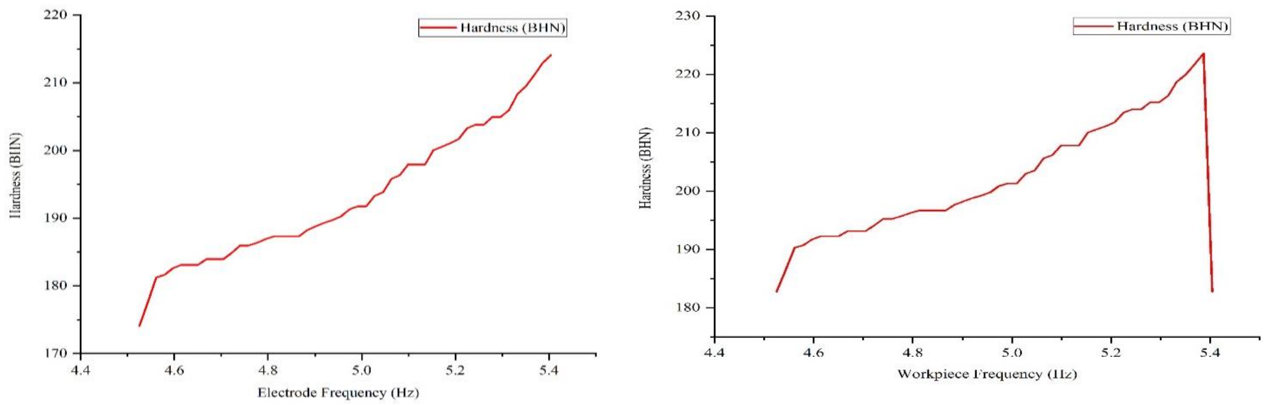


Fig. 2. Tensile Strength of butt joint under (a) electrode frequency (b) workpiece frequency

It can be observed from the fig. 2 that the increment in tensile strength with the increase of frequency of both electrode and workpiece. However, the fig. 2 (b) represents that the increase in the tensile strength is higher for the varying the workpiece frequency than the variation made in the electrode. The range of frequencies are found far higher in the electrode than the workpiece and the highest value of tensile strength is observed at 772 Mpa with the variation of electrode frequency at 800 Hz whereas 870 Mpa is shown at the frequency of 5.3 Hz with the variation of workpiece [17].

3.2. Hardness:

The variables are examined under the algorithm and produces the results about hardness strength of butt joint of SS304. It is given that the data is supplied for different frequences of the electrode, workpiece and possible improvement in the hardness of the weld joint is displayed by the algorithm. The obtained responses are plotted and represented in the fig. 3. The test is performed on Brinell Hardness Tester to validate the hardness of the vibratory welded specimens at highest possible enhancement and respective decrement with the further manipulation of the frequencies about workpiece and electrode.



(a) (b)

Fig. 3. Hardness of butt joint under (a) electrode frequency (b) workpiece frequency

It can be observed from the fig. 3 that the increment in hardness with the increase of frequency of both electrode and workpiece. However, the fig. 3 (b) represents that the increase in the hardness is higher for the varying the workpiece frequency than the variation made in the electrode. The range of frequencies are found far higher in the electrode than the workpiece and the highest value of hardness is observed at 213BHN with the variation of electrode frequency at 5.3 Hz whereas 223 BHN is shown at the frequency of 5.3 Hz with the variation of workpiece [18].

4. Microstructural Characterization:

The characterization tests are performed over the samples which are experimentally validated by implementing the results from the machine learning algorithm. The samples are made according to the ASTM standards and observed the results with the error rate of 5% for both the frequencies manipulated to the electrode, workpiece. The microstructure at the welded zone for tensile strength, hardness tested samples are characterized through SEM analysis. Etching process is performed by using 5% Nital reagent {HNO_3 (5ml) + ethyl alcohol (100ml)} over these samples in order to remove the blackspots and smoky layer created over the weld zone during the GMAW process. It can be observed from the fig. 4 (a) that the equal distribution of filler material into the weld zone made through GMAW process with the assistance of vibratory treatment.

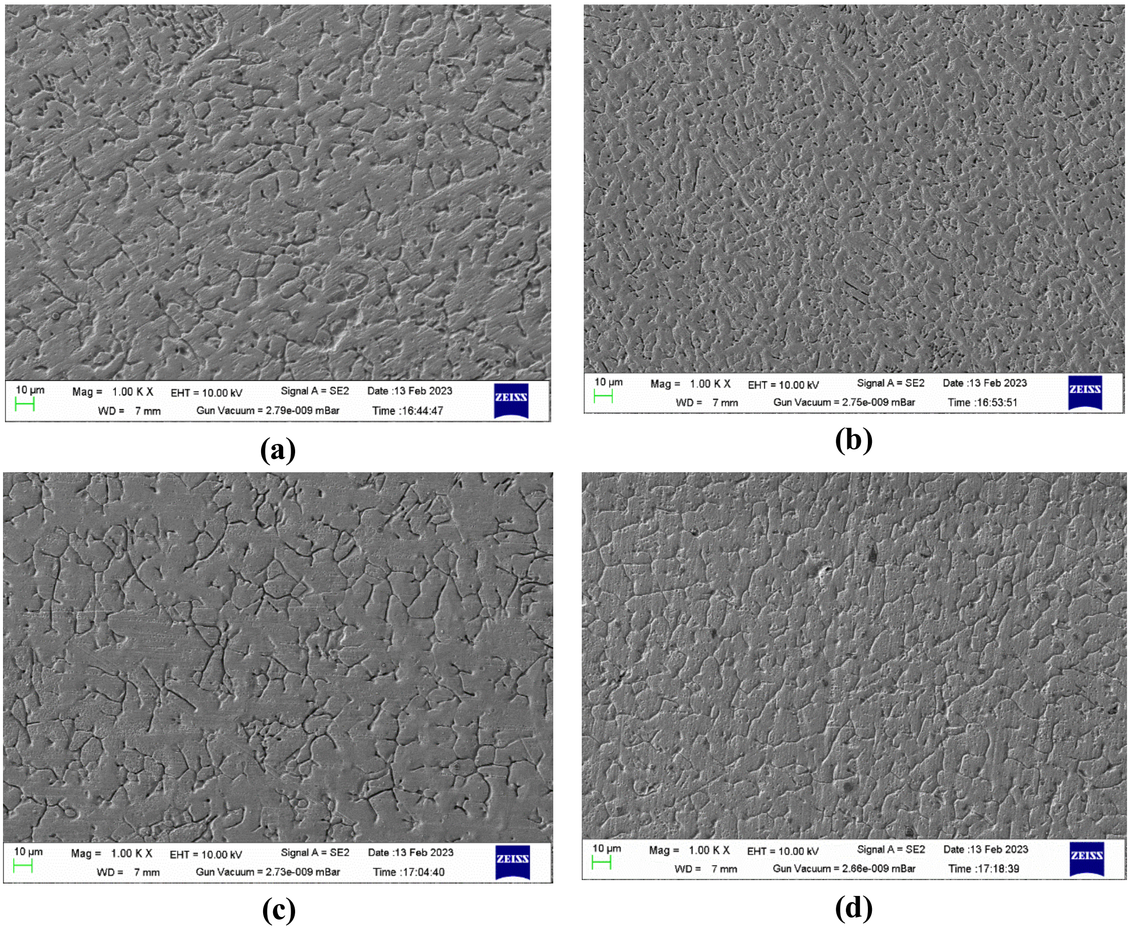


Fig. 4. Microstructures at various vibratory weld conditions **(a)** Tensile strength at 800 Hz with electrode vibration **(b)** Tensile strength at 5.3 Hz with workpiece vibration **(c)** Hardness at 5.3 Hz with electrode vibration **(d)** Hardness at 5.3 Hz with workpiece vibration

The effect of the higher frequencies employed during the welding process is clearly appeared in the samples shown in the fig. 4 (a)-(b) with the better distribution at uniform rate whereas the spurring of filler material with the excessive vibration might reduce the tensile strength in the sample than the lower frequencies with the vibration of workpiece. It is expected that the agitation of weldments in the weld pool can influence the solidification process [19-21]. Fig. 4 (c)-(d) represents the hardness tested samples made from GMAW process with vibration acceleration of 5.3 Hz for the electrode and workpiece frequencies individually. The improvements achieved in the effective distribution of filler material along with the base metal at the welded zone [22]. The broken dendritic structure during the hardness test is clearly appearing by the increased distribution of the solidified liquid of the fillet metal. However, the increase of vibration is further vibrated the liquid metal and contributed to the rate of liquid superheat which is generated from the welding heat [23,24].

5. Conclusion:

The research is aimed to identify optimal setting of parameters among frequency of workpiece, electrode at different power inputs through machine learning approach for the welding of SS304 in the gas metal arc welding (GMAW) process.

- The experiments were designed to run under different levels and the response in the improvement of weld strength is recorded in terms of mechanical properties.
- The variation in properties such as tensile strength, yield strength, flexural strength, hardness is observed at different frequencies and aimed to find the pareto optimal point to attain maximum enhancement in the weld strength.
- Experimental investigations are performed by selecting the parameter set at where the maximum enhancement is shown followed with the possible reduction at further increase of frequency on different properties.
- The rate of deviation is found at the average of 7.34% for all mechanical properties and pareto-optimal solution is with 5%.
- Characterization through SEM analysis is performed to analyze the grain refinement to improve weld strength at pareto-optimal set and the evidence is recorded.

References:

[1] Govindarao, P., P. Srinivasarao, A. Gopalakrishna, and M. Sarkar. "Affect of vibratory welding process to improve the mechanical properties of butt welded joints." *International journal of modern engineering research* 2, no. 4 (2012): 2766-2770.

[2] Rao, P. Govinda, P. Srinivasa Rao, and A. Gopala Krishna. "Mechanical properties improvement of weldments using vibratory welding system." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 229, no. 5 (2015): 776-784.

[3] Elsheikh, Ammar H. "Applications of machine learning in friction stir welding: Prediction of joint properties, real-time control and tool failure diagnosis." *Engineering Applications of Artificial Intelligence* 121 (2023): 105961.

[4] Balachandar, K., and R. Jegadeeshwaran. "Friction stir welding tool condition monitoring using vibration signals and Random forest algorithm–A Machine learning approach." *Materials Today: Proceedings* 46 (2021): 1174-1180.

[5] Mongan, Patrick G., Eoin P. Hinchy, Noel P. O'Dowd, and Conor T. McCarthy. "Quality prediction of ultrasonically welded joints using a hybrid machine learning model." *Journal of Manufacturing Processes* 71 (2021): 571-579.

[6] Vidal, Juan G., Germán O. Barrionuevo, Jorge A. Ramos-Grez, Julio Vergara, and José L. Mullo. "Vibration-assisted laser welding: Frequency and amplitude vibration effect on the microhardness of A36 steel." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 236, no. 10 (2022): 2139-2149.

[7] Das, Debasish, Amit Kr Das, D. K. Pratihar, and G. G. Roy. "Prediction of residual stress in electron beam welding of stainless steel from process parameters and natural frequency of vibrations using machine-learning algorithms." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235, no. 11 (2021): 2008-2021.

[8] Schwarz, Elisabeth Birgit, Fabian Bleier, Friedhelm Guenter, Ralf Mikut, and Jean Pierre Bergmann. "Improving process monitoring of ultrasonic metal welding using classical machine learning methods and process-informed time series evaluation." *Journal of Manufacturing Processes* 77 (2022): 54-62.

[9] Jang, Seungbeom, Wonjoo Lee, Yuhyeong Jeong, Yunfeng Wang, Chanhee Won, Jangwook Lee, and Jonghun Yoon. "Machine learning-based weld porosity detection using frequency analysis of arc sound in the pulsed gas tungsten arc welding process." *Journal of Advanced Joining Processes* 10 (2024): 100231.

[10] Satpathy, Mantra Prasad, Swayam Bikash Mishra, and Susanta Kumar Sahoo. "Ultrasonic spot welding of aluminum-copper dissimilar metals: a study on joint strength by experimentation and machine learning techniques." *Journal of Manufacturing Processes* 33 (2018): 96-110.

[11] Sabzi, Masoud, and Saeid Mersagh Dezfuli. "Drastic improvement in mechanical properties and weldability of 316L stainless steel weld joints by using electromagnetic vibration during GTAW process." *Journal of Manufacturing Processes* 33 (2018): 74-85.

[12] Singh, Pravin Kumar, D. Patel, and S. B. Prasad. "Optimization of process parameters during vibratory welding technique using Taguchi's analysis." *Perspectives in Science* 8 (2016): 399-402.

[13] Wang, Jianfeng, Qingjie Sun, Laijun Wu, Yibo Liu, Junbo Teng, and Jicai Feng. "Effect of ultrasonic vibration on microstructural evolution and mechanical properties of underwater wet welding joint." *Journal of Materials Processing Technology* 246 (2017): 185-197.

[14] Liu, X. C., C. S. Wu, and Girish Kumar Padhy. "Improved weld macrosection, microstructure and mechanical properties of 2024Al-T4 butt joints in ultrasonic vibration enhanced friction stir welding." *Science and Technology of Welding and Joining* 20, no. 4 (2015): 345-352.

[15] Yuvaraj, N., Jayanta Ghosh Roy, and Vipin. "Enhancement of microstructural and mechanical properties of ultrasonic vibration-assisted cold metal transfer welding of 304 stainless steel." *Journal of Materials Engineering and Performance* 31, no. 10 (2022): 8497-8511.

[16] Rao, P. Govinda, P. Srinivasa Rao, and A. Gopala Krishna. "Mechanical properties improvement of weldments using vibratory welding system." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 229, no. 5 (2015): 776-784.

[17] Lu, Qinghua, Ligong Chen, and Chunzhen Ni. "Improving welded valve quality by vibratory weld conditioning." *Materials Science and Engineering: A* 457, no. 1-2 (2007): 246-253.

[18] Qinghua, Lu, Chen Ligong, and Ni Chunzhen. "Effect of vibratory weld conditioning on welded valve properties." *Mechanics of Materials* 40, no. 7 (2008): 565-574.

[19] Watanabe, Takehiko, Masataka Shiroki, Atsushi Yanagisawa, and Tomohiro Sasaki. "Improvement of mechanical properties of ferritic stainless steel weld metal by ultrasonic vibration." *Journal of Materials Processing Technology* 210, no. 12 (2010): 1646-1651.

[20] Vykunta Rao, M., Srinivasa Rao P, and B. Surendra Babu. "Vibratory weld conditioning during gas tungsten arc welding of al 5052 alloy on the mechanical and micro-structural behavior." *World Journal of Engineering* 17, no. 6 (2020): 831-836.

[21] Serrati, Douglas Silva Marques, Ricardo Martins Silva, Jonas Guilherme Gomes Wiezel, Danilo Batista Cunha, Douglas Bezerra de Araújo, and Louriel Oliveira Vilarinho. "Effects of heat and vibration treatments for welding on residual stresses and mechanical properties." *The International Journal of Advanced Manufacturing Technology* 128, no. 3-4 (2023): 1473-1481.

[22] Bagheri, Behrouz, Mahmoud Abbasi, and Mostafa Dadaei. "Mechanical behavior and microstructure of AA6061-T6 joints made by friction stir vibration welding." *Journal of Materials Engineering and Performance* 29 (2020): 1165-1175.

[23] Tamasgavabari, Reza, Ali Reza Ebrahimi, Seyed Mehdi Abbasi, and Ali Reza Yazdipour. "The effect of harmonic vibration with a frequency below the resonant range on the mechanical properties of AA-5083-H321 aluminum alloy GMAW welded parts." *Materials Science and Engineering: A* 736 (2018): 248-257.

[24] Pal, Kaushik, Vinay Panwar, Sven Friedrich, and Michael Gehde. "An investigation on vibration welding of amorphous and semicrystalline polymers." *Materials and Manufacturing Processes* 31, no. 3 (2016): 372-378.