Optimization of Process Parameters in 3D Printing of SS304 Stainless Steel Using Wire Arc Additive Manufacturing with Cold Metal Transfer

M. Karthikeyan 1, A. Daniel Das2, B. Srinivasan3, C Ramesh Kannan4, P. Gopika5, V. Santhosh2,a)

1Department of Civil Engineering, Dhanalakshmi Srinivasan College of Engineering. Coimbatore 641105, Tamil Nadu, India

2Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, India

3Construction Management and Engineering, RVS Technical Campus, Coimbatore, Tamil Nadu, India

4Department of Mechanical Engineering, SRM TRP Engineering College, Tiruchirappalli, Tamil Nadu, India.

5Department of Management Studies, Karpagam College of Engineering, Coimbatore, Tamil Nadu, India

Corresponding Author: a)[santhoshshivan.v@gmail.com](mailto:santhoshshivan.v@gmail.com)

**Abstract:** This study focused on optimizing key parameters for wire-assisted arc additive manufacturing (WAAM) of SS304 stainless steel using cold metal transfer (CMT) technology. To improve process efficiency, three variableswelding current, traverse speed, and the gap between the contact tip and the workpiecewere systematically optimized. The Taguchi design method and gray relational analysis (GRA) were combined to determine optimal process conditions. The results showed that welding current had the greatest impact on process performance, while traverse speed and contact tip gap had relatively minor influences. The optimized parameter set provides important guidance for the application of WAAM in the manufacture of high-precision, high-durability SS304 stainless steel parts.

**Keywords**: 3D Printing, SS304, Wire Arc Additive Manufacturing, Cold Metal Transfer, Process Optimization, Taguchi Method, Gray Relational Analysis

# ****INTRODUCTION****

Most especially in metal parts fabrication, the use of 3D printing technology has made it easier to manufacture intricate designs more efficiently and with less scrap[1]. Out of many approaches, WAAM has emerged as one of the most used types of 3DP especially in a large, complex metal parts fabrication with high deposition rates[2,3,4,5]. Unlike conventional additive manufacturing methods that use a focused laser beam as a heat source, wire arc additive manufacturing (WAAM) uses an electric arc for melting and a continuous wire feed to fill the material, effectively combining the versatility of 3D printing with the robustness of welding technology [6]. This technology has shown great potential when applied to stainless steel, especially austenitic SS304 stainless steel. SS304 stainless steel is widely used in the aerospace, marine, and automotive industries due to its excellent ductility, mechanical strength, and corrosion resistance [7–10]. Despite these advantages, obtaining uniform and defect-free SS304 parts using WAAM remains a challenging task. Key process parameters such as welding current, feed speed, and the distance between the contact tip and the workpiece play an important role in determining the surface finish, interlayer bonding, and residual stress levels of the final structure. [11-13]. These parameters are self-explanatory and are known to bear various mutual influences on the characteristics of the product. While if these many factors are not systematically optimized then the mechanical performance can be far from optimum and which inhibits the potential use of WAAM process for high standard industrial application[14].Current research on the WAAM based on 3D printing of stainless steel are mainly based on single response performances or precise control of parameter values, which cannot meet the multi-response engineering requirements[15-19]. This research fills this gap by applying a dual optimization technique that incorporates Taguchi and the Gray Relational Analysis (GRA) to model SS304 components and attain multi-objective optimization[20-25]. This work presents a holistically better optimization approach in comparison to the previous research studying only one quality parameter at a time, ready to offer better WAAM process control and better application to the industrial environment[26-31]. The primary objective of this study is to examine and summarize the current advancements in the application of WAAM for fabricating SS304 stainless steel components.The subject of this work is Cold Metal Transfer (CMT), a variation of the WAAM process that minimizes heat input and spatter. In this current study, we will use Taguchi’s orthogonal array design with GRA to set the current, welding speed and CTWD with an aim of optimizing the deposition quality, structural uniformity and finally an overall improvement in the performance of the welded component [32-35]. Therefore, the aim of this research is to lay the groundwork for achieving these optimal parameters concerning large-scale 3D printed metal parts to enhance the yield rate of SS304 components through WAAM technology that could potentially cut down the production costs and time for parts manufacturing in the industry.

# ****EXPERIMENTAL** **PROCEDURE****

In this study, we used a design of experiments (DOE) to investigate the effects of WAAM and CMT processes on 3D printing of SS304 stainless steel. For the DOE, we selected a nine-level orthogonal matrix, considering three key variables: feed rate (WS), welding current (I) and contact tip to base distance (CTWD). Table 1 summarizes the selected factor levels for each variable.

Table 1:Independent Input Parameters and Levels

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Unit** | **Level 1** | **Level 2** | **Level 3** |
| Current (I) | A | 95 | 105 | 115 |
| Welding Speed (WS) | m/min | 0.4 | 0.5 | 0.6 |
| Contact Tip to Work Distance (CTWD) | mm | 2.0 | 2.5 | 3.0 |

Each of the nine experimental runs was designed in accordance with the L9 orthogonal array to study the effects exerted by certain parameters on SS304 deposition quality. These parameter combinations shown in Table 2 were aimed at creating build samples using controlled WAAM-CMT conditions.

Table 2: Experimental design - L9 orthogonal array representing the combinations of input parameters.

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Current (A)** | **Welding Speed (m/min)** | **CTWD (mm)** |
| 1 | 95 | 0.4 | 2.0 |
| 2 | 95 | 0.5 | 2.5 |
| 3 | 95 | 0.6 | 3.0 |
| 4 | 105 | 0.4 | 2.5 |
| 5 | 105 | 0.5 | 3.0 |
| 6 | 105 | 0.6 | 2.0 |
| 7 | 115 | 0.4 | 3.0 |
| 8 | 115 | 0.5 | 2.0 |
| 9 | 115 | 0.6 | 2.5 |

# MATERIALS AND EXPERIMENTAL WORK

This study fabricated SS304 stainless steel components using wire arc additive manufacturing technology, integrated with a 6-axis KuKa robot system (model KR8R1440, Germany) equipped with a Kobe welder and a Pronius cold metal transfer (CMT) power source (model TPS400i, Austria). Preliminary experiments were conducted to determine the operating ranges for fundamental process variables, including welding current, welding stroke, and contact tip to base metal distance (CTWD), as these variables significantly impact deposition uniformity, arc stability, and overall weld quality. The interdependence of current, voltage, and wire feed speed in the CMT process limits the ability to adjust each variable independently. Therefore, based on experimental evidence and existing literature, welding current was selected as the primary variable. Among the variables studied, welding speed has been shown to significantly influence weld bead shape and structural integrity, while CTWD has been identified as a key factor in achieving stable arc speed conditions and a well-defined weld bead shape. The shielding gas composition and flow rate were also carefully optimized, as they significantly influence the microstructural characteristics of the deposited material. A high-purity gas mixture consisting of 97% argon and 3% carbon dioxide was used at a flow rate of 15 liters per minute to minimize dilution effects in the weld pool [36-40]. A 1.2 mm diameter SS304 filler wire was used during deposition, and the substrate consisted of 200 × 50 × 6 mm SS304 sheet. Prior to deposition, each substrate was thoroughly cleaned with acetone to remove surface contaminants and ensure a stable metallurgical bond throughout the build.

## Gray Relational Analysis for Multi-Response Optimization

This study combined Taguchi's experimental design with grey relational analysis (GRA) to perform multi-reaction optimization of process variables in the wire arc additive manufacturing (WAAM) of SS304 stainless steel. The core advantage of GRA lies in its ability to simultaneously optimize multiple reaction variables, thereby ensuring a balanced improvement in overall process performance. The reaction table generated by the Taguchi method provides the necessary dataset for constructing the GRA framework [41-45]. Unlike traditional methods that adjust each factor individually to achieve a target value, this method focuses on the comprehensive performance of all reaction variables, providing a more systematic and reliable optimization strategy.

## Data Pre-processing

Data preprocessing is the initial stage of Gray Relational Analysis (Gray) and is crucial for preparing the response data required for subsequent evaluation. The primary goal of data preprocessing is to resolve differences in units and scales between different response parameters to facilitate meaningful comparisons. This step consists of two main steps. The first step is to convert the raw experimental data into a signal-to-noise ratio (S/N) to minimize variability and increase robustness. This conversion allows each response to be expressed on a comparable scale. For experiments using the L9 orthogonal array, the S/N value is calculated using a "larger is better" criterion, which is appropriate for optimizing efficiency-related responses [46-48].After calculating the S/N ratio, a normalization procedure is applied to map all values to a dimensionless range between 0 and 1. This conversion eliminates the effects of different units and ensures fair comparisons between responses. Normalized values closer to 1 indicate better performance for that response. The normalized data set was used to derive the grey relational coefficient (GRC), which served as the basic criterion for classifying and optimizing the process parameters in the next analysis stage.

## Gray Relational Coefficient, Grade, and Rank

Table 3. Experimental results of microhardness, ultimate tensile strength (UTS), and residual stress.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **Current (A)** | **Welding Speed (m/min)** | **CTWD (mm)** | **Microhardness (HV)** | **UTS (MPa)** | **Residual Stress (MPa)** |
| 1 | 95 | 0.4 | 2.0 | 256.25 | 562.77 | -75.33 |
| 2 | 95 | 0.5 | 2.5 | 258.75 | 563.34 | -97.32 |
| 3 | 95 | 0.6 | 3 | 269.37 | 583.88 | -56.33 |
| 4 | 100 | 0.4 | 2.5 | 233.35 | 587.22 | -129.33 |
| 5 | 100 | 0.5 | 3.0 | 236.75 | 598.88 | -69.66 |
| 6 | 100 | 0.6 | 2.0 | 257.75 | 527.22 | -144.18 |
| 7 | 105 | 0.4 | 3.0 | 220.25 | 505.00 | -108.33 |
| 8 | 105 | 0.5 | 2.0 | 236.50 | 491.00 | -120.25 |
| 9 | 105 | 0.6 | 2.5 | 238.00 | 573.33 | -87.66 |

The normalized data set was used to calculate the Grey Relational Coefficient (GRC), which quantifies how well each experimental run matched the ideal reference target. Higher GRC values indicate stronger correlation with the target outcome, while lower values indicate weaker fit. Therefore, the GRC is an important indicator of response efficiency relative to a given reference level and can be used to evaluate parameter performance within each experimental run.Once the GRC value is determined, the Grey Relational Rank (GRG) is calculated by summing the coefficients corresponding to all response variables [49-52]. The GRG provides a comprehensive metric for categorizing experimental runs and enabling a comprehensive assessment of process performance. Experiments with higher GRG values are considered superior because they represent parameter combinations that effectively balance multiple response targets. Therefore, the GRG can serve as a reliable criterion for selecting optimal process parameters when producing SS304 stainless steel using WAAM.Table 3 lists the experimental results, including microhardness, ultimate tensile strength (UTS), and residual stress [54-55]. Additionally, Table 4 summarizes the calculated signal-to-noise ratio for each response and its normalized value.

# Results and Discussion

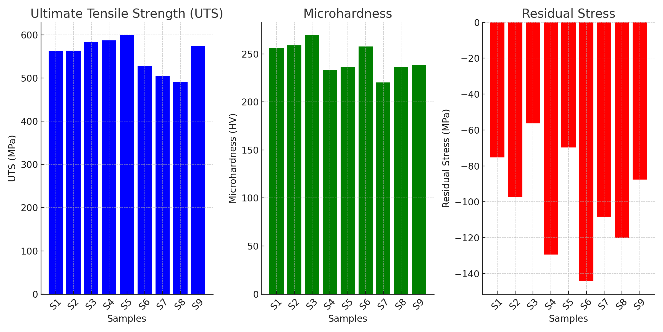
In this study, SS304 stainless steel samples were fabricated using wire arc additive manufacturing (WAAM) and cold metal transfer (CMT) processes, depositing a total of 40 layers. Heat input, determined by process variables such as welding current and travel speed, is considered a key factor influencing both individual layer thickness and total thickness. Specifically, maximum heat input is observed when the maximum current is combined with the lowest welding speed. Prior to mechanical property evaluation, the deposited samples were surface ground to improve surface finish and achieve uniform roughness. Detailed specifications of the samples fabricated using CMT-WAAM are summarized in Table 7.

## Mechanical Properties

This study evaluated the mechanical properties of all prepared samples, including ultimate tensile strength (UTS), microhardness (MH), and residual stress (RS). Nine representative samples were analyzed in detail, as shown in Figure 1 and Table 4. The UTS values, summarized in Table 2, show considerable variation. Sample 5 achieved an UTS of 599 MPa, while Sample 8 achieved the lowest value, at 491 MPa. The UTS values for the remaining samples ranged from 505 MPa to 587 MPa, representing approximately 85.6% to 99.4% of the strength of conventionally rolled SS304 stainless steel (590 MPa). All tensile tests were conducted in the transverse direction, which is generally considered the weakest direction in additively manufactured materials.The average yield strength (YS) of the prepared samples was approximately 290 MPa, significantly higher than the typical YS of conventionally machined SS304 stainless steel (approximately 230 MPa). These improvements clearly demonstrate the strengthening effect of the WAAM-CMT process. The stress-strain behavior of the deposited samples, shown in Figure 1, also demonstrates elongations ranging from 43.8% to 59.6%. While this ductility is slightly lower than the typical elongation of approximately 48% for wrought stainless steel, it confirms that the prepared samples retain significant plastic deformation capacity [53].Overall, these results demonstrate that the WAAM-CMT process not only achieves tensile properties similar to those of existing SS304 stainless steel but, in some cases, even exceeds them, particularly in terms of yield strength.

Table 4: Signal-to-noise (S/N) ratios and corresponding normalized S/N ratio values.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **S/N Ratio - Microhardness (dB)** | **S/N Ratio - UTS (dB)** | **S/N Ratio - Residual Stress (dB)** | **Normalized Microhardness** | **Normalized UTS** | **Normalized Residual Stress** |
| 1 | 51.81 | 58.85 | 41.15 | 0.71 | 0.64 | 0.34 |
| 2 | 52.01 | 59.11 | 43.25 | 0.75 | 0.68 | 0.52 |
| 3 | 52.32 | 59.90 | 39.45 | 0.82 | 0.85 | 0.21 |
| 4 | 50.83 | 60.02 | 46.37 | 0.54 | 0.87 | 0.81 |
| 5 | 51.02 | 60.21 | 41.89 | 0.58 | 0.91 | 0.39 |
| 6 | 52.12 | 57.61 | 48.72 | 0.76 | 0.42 | 1.00 |
| 7 | 49.62 | 57.21 | 44.15 | 0.31 | 0.31 | 0.65 |
| 8 | 50.92 | 56.75 | 45.31 | 0.57 | 0.21 | 0.74 |
| 9 | 51.15 | 59.63 | 42.68 | 0.63 | 0.79 | 0.45 |



**Figure 1:**Ultimate tensile strength (UTS), microhardness, and residual stress of WAAM-fabricated SS304 samples under different process parameter conditions.

Microhardness samples were determined at four bottom to top locations (1-4) taking ten parallel horizontal measurements at each location for average characterization. The obtained microhardness was measured in the range of 220 to 257 HV, characterizing the vertical microhardness profile of the material. High hardness of the base region is explained by the quenching effect of the substrate, which rapidly removes heat from the surface towards the base, thus creating a situation of gradually decreasing hardness from the base to the surface of the sample. That all the specimens have similar microhardness values but are significantly higher in each zone means that even where there are differences in hardness, there is consistent structure, which minimizes the chance of failure through brittleness.

**Table 5:**Gray relational coefficients, grades, and corresponding ranks of the samples.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Coefficient – Microhardness** | **Coefficient – UTS** | **Coefficient – Residual Stress** | **Overall Gray Relational Grade** | **Performance Rank** |
| S1 | 0.63 | 0.58 | 0.43 | 0.55 | 6 |
| S2 | 0.67 | 0.61 | 0.51 | 0.60 | 5 |
| S3 | 0.73 | 0.77 | 0.39 | 0.63 | 4 |
| S4 | 0.52 | 0.79 | 0.73 | 0.68 | 3 |
| S5 | 0.55 | 0.83 | 0.45 | 0.61 | 5 |
| S6 | 0.68 | 0.46 | 1.00 | 0.71 | 2 |
| S7 | 0.42 | 0.42 | 0.59 | 0.47 | 9 |
| S8 | 0.54 | 0.39 | 0.67 | 0.53 | 7 |
| S9 | 0.59 | 0.72 | 0.47 | 0.59 | 6 |

## Analysis of Residual Stress

The residual stress distribution along three perpendicular planes of the as-fabricated components was evaluated. Starting from the substrate (position 1) and extending upward to positions 2 and 3, five measurements were taken on each plane, and the average values were calculated. The interaction between high heat input and rapid solidification has been shown to produce compressive residual stresses, which generally improve the fatigue resistance of WAAM structures. Conversely, tensile residual stresses, typically generated under tensile loading, can have a detrimental effect, promoting crack initiation and propagation, ultimately leading to premature failure. The results show that the highest compressive stresses are concentrated near the substrate region (position 1), where stress accumulates at the interface, while tensile residual stresses are more pronounced in the upper regions of the structure. Overall, the measurements confirm that WAAM components tend to develop tensile residual stresses, which gradually increase with increasing fabrication height. Table 4 reports the average residual stress values corresponding to the three perpendicular positions.

## Analysis of Variance (ANOVA) Applied to Gray Relational Optimization

The mechanical properties of the WAAM samples were statistically examined using analysis of variance (ANOVA), a powerful method for determining the impact of various process variables. This method decomposes the overall variation in the grayscale into the contributions of controllable factors and experimental error by calculating the mean squared deviation. The contribution percentage of each variable is then derived to assess its relative influence on the mechanical response. Based on the ANOVA results, welding current (I), welding speed (WS), and tip-to-workpiece contact velocity (CTWD) contribute approximately 76%, 21%, and 3%, respectively, to the overall variation in the grayscale. This confirms that current is the most significant variable influencing the mechanical behavior of WAAM SS304, followed by welding speed, with CTWD having a minimal effect.

Table 6: Response table of gray relational grades for WAAM SS304 process parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Factors** | **Level 1** | **Level 2** | **Level 3** | **Delta** | **Rank** |
| Current (I) | 0.59 | 0.66 | 0.56 | 0.10 | 1 |
| Welding Speed (WS) | 0.55 | 0.57 | 0.67 | 0.12 | 2 |
| CTWD | 0.60 | 0.63 | 0.56 | 0.07 | 3 |

Table 7: Confirmation Test Results

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter Settings** | **Initial (Sample S6)** | **Optimal (Predicted)** | **Confirmation (Experiment)** |
| Current (I) | 105 A | 105 A | 105 A |
| Welding Speed (WS) | 0.8 m/min | 0.8 m/min | 0.8 m/min |
| Contact Tip to Work Distance (CTWD) | 2.0 mm | 2.8 mm | 2.8 mm |
| Ultimate Tensile Strength (UTS, MPa) | 522.64 | 590.12 | 587.45 |
| Microhardness (MH, HV) | 255.23 | 267.51 | 265.87 |
| Residual Stress (MPa) | -139.87 | -118.33 | -120.21 |
| Gray Relational Grade | 0.71 | 0.75 | 0.74 |
| Improvement in Grade | — | 0.04 | 0.03 |

## Confirmation Test

To verify the improved mechanical properties of the CMT-WAAM specimens, we conducted validation experiments using the optimal parameter combinations shown in Table 6. These optimized settings were chosen to match the improvements observed during the multi-response optimization process. In the validation experiments, the input parameters were set to their optimal levels to demonstrate their significant impact on the mechanical properties of the WAAM specimens. The results, summarized in Table 7, show that the grayscale obtained under the optimal parameter conditions is significantly higher than that obtained in the initial experiments, confirming the overall performance improvement.

# Conclusion

The results of this investigation confirm that WAAM is a highly effective and economical additive manufacturing route, particularly suited for the fabrication of large components due to its high deposition efficiency. The incorporation of Cold Metal Transfer (CMT) technology plays a crucial role in improving build quality by reducing typical defects, especially cracking associated with heat accumulation and steep temperature gradients. In this study, the influence of three input factors—current (I), welding speed (WS), and contact tip to workpiece distance (CTWD)—was examined for SS316L stainless steel components. The experimental design was structured using Taguchi’s L9 orthogonal array, and the optimization of responses was carried out through Gray Relational Analysis (GRA). The key findings are summarized below:

1. Using GRA, the optimal parameter combination for maximizing ultimate tensile strength (UTS), microhardness (MH), and residual stress (RS) was identified. The best performance was obtained at 110 A current, 0.7 m/min welding speed, and 3 mm CTWD.
2. The ANOVA of gray relational grades (Table 7) showed that welding current had the highest influence on mechanical properties, contributing the most to overall variation, followed by welding speed and CTWD.
3. At the optimized parameter levels, UTS and MH exhibited significant improvements, while RS showed a slight reduction. The confirmation test further validated the optimization, with an increase of 0.036 in the gray relational grade compared to the initial trials.

# References

1. Leif. Welding duplex stainless steel—A review of current recommendations. *Weld World* 2012; 56: 65–76.
2. Kumar P, Maji K. Experimental investigations and parametric effects on depositions of super duplex stainless steel in wire arc additive manufacturing. *Proc Inst Mech Eng E* 2023: 095440892311582.
3. Sales A, Kotousov A, Yin L. Design against fatigue of super duplex stainless steel structures fabricated by wire arc additive manufacturing process. *Metals (Basel)* 2021; 11: 1965.
4. Zhang Y, Wu S, Cheng F. A specially designed super duplex stainless steel with balanced ferrite:austenite ratio fabricated via flux-cored wire arc additive manufacturing: Microstructure evolution, mechanical properties, and corrosion resistance. *Mater Sci Eng A* 2022; 854: 143809.
5. Horgar A, Fostervoll H, Nyhus B, et al. Additive manufacturing using WAAM with AA5183 wire. *J Mater Process Technol* 2018; 259: 68–74.
6. Köhler M, Sun L, Hensel J, et al. Comparative study of deposition patterns for DED-arc additive manufacturing of Al-4046. *Mater Des* 2021; 210: 110122.
7. Motwani A, Kumar A, Talekar A, et al. Process parameters optimization for cold metal transfer-deposited IN625 single-layer bead features by entropy weightage-assisted grey-based Taguchi analysis. *Proc Inst Mech Eng E* 2023: 095440892211501.
8. Koppu AK, Motwani A, Lautre NK, et al. Performance evaluation of interfacial characteristics between cold metal transfer-wire arc additive manufactured SS308LSi and wrought SS304L with controlled and uncontrolled inter-layer temperature. *Proc Inst Mech Eng E*, Epub ahead of print 4 September 2023. doi: 10.1177/09544089231199223.
9. Lee SH. CMT-based wire arc additive manufacturing using 316L stainless steel: Effect of heat accumulation on the multi-layer deposits. *Metals (Basel)* 2020; 10: 278.
10. Pickin CG, Williams SW, Lunt M. Characterisation of the cold metal transfer (CMT) process and its application for low dilution cladding. *J Mater Process Technol* 2011; 211: 496–502.
11. Joshi GR, Badheka VJ, Darji RS, et al. The joining of copper to stainless steel by solid-state welding processes: A review. *Materials (Basel)* 2022; 15: 7234.
12. Khuri AI, Mukhopadhyay S. Response surface methodology. *WIRES Comput Stat* 2010; 2: 128–149.
13. Babu et al., (2024). Enhancing Security with Machine Learning-based Finger-Vein Biometric Authentication System. In 2024 5th International Conference on Mobile Computing and Sustainable Informatics (ICMCSI)(pp. 797-802). IEEE. https://doi.org/[10.1109/ICMCSI61536.2024.00123](https://doi.org/10.1109/ICMCSI61536.2024.00123)
14. I. Hossain et al. (2025). Enriching performance of Al-Mg composites by incorporating nano-alumina and SiC via semi-solid stir processing. International Journal of Cast Metals Research, 1–11. <https://doi.org/10.1080/13640461.2025.2476826>
15. ManzooreElahi M. Soudagar, et al. Enrichment of Solar Heat Exchanger Thermal Performance by the Integration of Beeswax and Hybrid Nanofluid (ZnO/MgO). ASME. J. Thermal Sci. Eng. Appl. (2025) <https://doi.org/10.1115/1.4067929>
16. P. K. Singh et al. Enhancement of silicon nitride layer performance by Gallium–Copper–Zinc tri-layer thin films structure via plasma featured chemical vapour deposition route. J Mater Sci: Mater Electron 36, 243 (2025). <https://doi.org/10.1007/s10854-025-14326-9>
17. R, Rajarajan et al. (2025). Improving Tribological Performance and Structural Analysis of Aluminium Hybrid Nanocomposites with Nano ZrO2/SiC Reinforcement via Stir Casting Assisted with Ultrasonic Vibration. International Journal of Cast Metals Research, February, 1–14. <https://doi.org/10.1080/13640461.2025.2467611>
18. Soudagar, M. ManzooreElahi et al. Effect of electron transport layer thickness and characteristics behaviour of hybrid copper indium gallium selenide thin film solar cells, Journal of Power Sources (2025). Volume 639, 2025,236657, <https://doi.org/10.1016/j.jpowsour.2025.236657>
19. M. Aruna et al. Vacuum Die Casting Process and Microstructure/Mechanical Characteristics Study of Magnesium Alloy Composite Hybridize with Zirconium Dioxide and Silicon Nitride. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01550-6>
20. V.V. Upadhyay et al. Trapezoidal fin featured heat exchanger performance enriched by using alumina/GNP hybrid nanofluid: thermal characteristics study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-13997-0>
21. P. K. Singh et al. Integration of phase change material for enriching the solar collector featured with dryer configuration enhanced via alumina/titanium dioxide nanoparticle: performance study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14302-9>
22. ManzooreElahi M. Soudagar, RavindraPratap Singh, NagabhooshanamNagarajan. et al. Featuring of in-situ carbon capturing and functional performance study of hydrogen from aquaculture wastewater algae biomass via supercritical steam gasification route, Chemical Engineering Science 313 (2025) 121704. <https://doi.org/10.1016/j.ces.2025.121704>
23. JothiArunachalam et al. Integration of nanographene and action of fiber sequences on functional behaviour of composite laminates" International Polymer Processing, 2025. <https://doi.org/10.1515/ipp-2024-0149>
24. P. P. Singh et al. Hybrid Thin Film Coating Performance and Functional Characteristics of Silicon Nitride (SiNx) Layer for Solar Cell Application. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11888-6>
25. N. Nagarajan et al. Hybrid Stir Cast Featured with Wettability Agent and Ultrasonic Action of Magnesium Alloy Composite Composed with Nanofiller: Study Characteristics. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01603-w>
26. V. Mohanavel et al. Tribological characteristics and optimization of ZrB2 configured magnesium alloy composite via squeeze casting technique. J MechSci Technol. 39(5), 2025. <https://doi.org/10.1007/s12206-025-0425-9>
27. ManzooreElahi M. Soudagar et al. Higher performance solar air dryer functioned with palmitic acid phase change material and hybrid nanofluid: Thermal performance evaluation, Applied Thermal Engineering (2025). Volume 272, 2025,126413, <https://doi.org/10.1016/j.applthermaleng.2025.126413>
28. P. P. Singh et al. Hybrid Thin Film Coating Performance and Functional Characteristics of Silicon Nitride (SiNx) Layer for Solar Cell Application. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11888-6>
29. N. Nagabhooshanam et al. Influences of Potassium Fluoride and Ultrasonic Vibration on Functional Performance of AZ91 Alloy Hybrid Nanocomposite with Nano-SiC/TiO2. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01552-4>
30. Ahmad et al., (2024). IoT-Enabled Smart E-Healthcare System with Predictive Prescription Algorithm for Automatic Patient Monitoring and Treatment. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1076-1081). IEEE. https://doi.org/[10.1109/ICPCSN62568.2024.00179](https://doi.org/10.1109/ICPCSN62568.2024.00179)
31. Saadh M J et al., (2024). Recent progress and the emerging role of lncRNAs in cancer drug resistance; focusing on signaling pathways. Pathology-Research and Practice, 253, 154999. <https://doi.org/10.1016/j.prp.2023.154999>
32. Lakshmaiya, N. (2024). High ionic permeability of Piper ION membrane boosts efficiency in CO2 electrolysis cells. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 172-180). SPIE. <https://doi.org/10.1117/12.3030841>
33. Kaushal et al., (2024). Evaluation of Deep Learning Approaches for Air Quality Analysis using an Image Dataset. In 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI) (pp. 1378-1383). IEEE. https://doi.org/[10.1109/ICoICI62503.2024.10696429](https://doi.org/10.1109/ICoICI62503.2024.10696429)
34. Anitha, Cuddapah, Naveena Kumar RR, SwapnilUttamraoDeokar, Harshal Shah, and Praful V. Nandankar. Optimal Scheduling of Microgrid with Electric Vehicle Integration in Smart Grid using Progressive Graph Convolutional Network. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 375-380. IEEE, 2025.
35. N. Nagarajan. et al. Thermal performance assessment of dish collector-integrated cooking application using TiO2/SiO2 hybrid nano-enhanced coated receiver. J Braz. Soc. Mech. Sci. Eng. 47, 148 (2025). <https://doi.org/10.1007/s40430-025-05454-8>
36. A. Sharma et al. Hybrid Reinforcement Actions on Microstructural, Physical and Mechanical Properties of Magnesium Alloy Composite by Two-Step Stir Casting Process. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-024-01537-9>
37. P. Sharma et al. Effect of paraffin with salt hydrates PCM and hybrid Al2O3/Tio2 nanofluid on thermal and energy storage characteristics of solar thermal heat exchanger. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14224-6>
38. M. Aruna et al. Integration of Magnesium Fluoride and Nano Alumina–Silicon Carbide Actions on Properties of AZ91 Alloy Hybrid Nanocomposites. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01617-4>
39. A. Sharma et al. Structural Modification and Enhancement of Optoelectronic Behaviour of ZnO Nanofilms Featuring Cu and Ti Particles. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11951-2>
40. Socrates, S., Bharathi, G. B., &Aluvala, S. (2024). A Framework for Automated Diagnosis and Management of Autoimmune Disorders with Neural Networks. In 2024 International Conference on Advancements in Smart, Secure and Intelligent Computing (ASSIC) (pp. 1-6). IEEE. https://doi.org/[10.1109/ASSIC60049.2024.10507903](https://doi.org/10.1109/ASSIC60049.2024.10507903)
41. Selvan et al., (2024). Investigation of the Use of Renewable Energy in Microgrid Applications. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE . https://doi.org/10.1109/ICONSTEM60960.2024.10568631
42. Vinodh, D et al., (2024). Experimental investigation on tensile strength of novel metal matrix composite of aluminium alloy 5083 with SiC and eggshell powder reinforcement. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 297-306). SPIE.  https://doi.org/10.1117/12.3030843
43. Kalam, S. A., Sheela, S., Paramasivam, P., &Shanmugam, K. (2024). Bio-synthesis of nano-zero-valent iron using barberry leaf extract: classification and utilization in the processing of methylene blue-polluted water. Discover Applied Sciences, 6(12), 1-15. https://doi.org/10.1007/s42452-024-06327-w
44. Lakshmaiya, N. (2024). Detection and impact of stochastic anomalies in investigations of urban pollution. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 269-277). SPIE. <https://doi.org/10.1117/12.3030839>
45. Padhy et al., (2024). Enhancing IoT-Enabled Healthcare with Genetic-based Encryption and Authentication for Secure and Efficient wireless Data Transmission. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1873-1878). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544722
46. Rafi et al., (2024). Improving Prostate Cancer Diagnosis with Weakly Supervised Learning and Radiology-Confirmed Negative MRI Data. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1183-1188). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544551
47. Agrawal et al., (2024). Deep Learning Methods for Detecting ImageBased Defects in Manufacturing Processes. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568644
48. Lakshmaiya, N. (2024). Influence of small non-capillary washing activity on flow boiling essential heat transfer. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 224-231). SPIE.  https://doi.org/10.1117/12.3030838
49. Singh et al., (2024). Enhancing Mobile Robot Speed Control: PID Controller Optimization with Bio-Inspired Algorithms. In 2024 International Conference on Expert Clouds and Applications (ICOECA) (pp. 365-370). IEEE. https://doi.org/10.1109/ICOECA62351.2024.00071
50. Chakrapani et al., (2024). Optimizing sample length for fault diagnosis of clutch systems using deep learning and vibration analysis. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089241272791. https://doi.org/10.1177/095440892412727
51. Deepthi et al., (2024). Deep Learning-Enabled Human Resource Analytics in Predicting Employee Performance. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). EEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568716
52. Ali, H. M., Mothilal, T., & Reddy, V. (2024). Evaluation of Lightweight Cotton Textiles for Durable and Comfortable Automotive Interior Applications (No. 2024-01-5015). SAE Technical Paper. DOI: https://doi.org/10.4271/2024-01-5015
53. Kelagadi et al., (2024). An Analysis on the Integration of Machine Learning and Advanced Imaging Technologies for Predicting the Liver Cancer. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1082-1086). IEEE. <https://doi.org/10.1109/ICPCSN62568.2024.00180>
54. Raja, S., Ali, R. M., Babar, Y. V., Surakasi, R., Karthikeyan, S., Panneerselvam, B., & Jagadheeswari, A. S. (2024). Integration of nanomaterials in FDM for enhanced surface properties: Optimized manufacturing approaches. Applied Chemical Engineering, 7(3).
55. Raja, S., Ali, R. M., Karthikeyan, S., Surakasi, R., Anand, R., Devarasu, N., & Sathish, T. (2024). Energy-efficient FDM printing of sustainable polymers: optimization strategies for material and process performance. Applied Chemical Engineering, 7(5537), 10–59429.

. Leif. Welding duplex stainless steel —a review of current

recommendations. Weld World 2012; 56: 65–76.

2. Kumar P and Maji K. Experimental investigations and para-

metric effects on depositions of super Duplex stainless steel

in wire arc additive manufacturing. Proc Inst Mech Eng E

2023: 095440892311582.

3. Sales A, Kotousov A and Yin L. Design against fatigue of

super Duplex stainless steel structures fabricated by wire

arc additive manufacturing process. Metals (Basel) 2021;

11: 1965.

4. Zhang Y, Wu S and Cheng F. A specially-designed super

duplex stainless steel with balanced ferrite:austenite ratio

fabricated via ﬂux-cored wire arc additive manufacturing:

microstructure evolution, mechanical properties and corro-

sion resistance. Mater Sci Eng A2022; 854: 143809.

5. Horgar A, Fostervoll H, Nyhus B, et al. Additive manufac-

turing using WAAM with AA5183 wire. J Mater Process

Technol 2018; 259: 68–74.

6. Köhler M, Sun L, Hensel J, et al. Comparative study of

deposition patterns for DED-arc additive manufacturing of

Al-4046.Mater Des 2021; 210: 110122.

7. Motwani A, Kumar A, Talekar A, et al. Process parameters

optimization for cold metal transfer-deposited IN625 single-

layer bead features by entropy weightage-assisted grey-

based Taguchi analysis. Proc Inst Mech Eng E 2023:

095440892211501.

8. Koppu AK, Motwani A, Lautre NK, et al. Performance

evaluation of interfacial characteristics between cold metal

transfer-wire arc additive manufactured SS308LSi and

wrought SS304L with controlled and uncontrolled inter-

layer temperature. Proc Inst Mech Eng E, Epub ahead of

print 4 September 2023. doi: 10.1177/09544089231199223.

9. Lee SH. CMT-based wire arc additive manufacturing using

316L stainless steel: effect of heat accumulation on the

multi-layer deposits. Metals (Basel) 2020; 10: 278.

10. Pickin CG, Williams SW and Lunt M. Characterisation of

the cold metal transfer (CMT) process and its application

for low dilution cladding. J Mater Process Technol 2011;

211: 496–502.

11. Joshi GR, Badheka VJ, Darji RS, et al. The joining of

copper to stainless steel by solid-state welding processes:

a review. Materials (Basel) 2022; 15: 7234.

12. Khuri AI and Mukhopadhyay S. Response surface method-

ology. WIRES Comput Stat 2010; 2: 128–149.

13. Chelladurai SJS, Murugan K, Ray AP, et al. Optimization of

process parameters using response surface methodology:

a review. Mater Today Proc 2021; 37: 1301–1304.

14. Zhang Z, Yan J, Lu X, et al. Optimization of porosity and

surface roughness of CMT-P wire arc additive manufactur-

ing of AA2024 using response surface methodology and

NSGA-II.J Mater Res Technol 2023; 24: 6923–6941.

15. Prasanna Nagasai B, Malarvizhi S and Balasubramanian V.

A study on wire arc additive manufacturing of 308L austen-

itic stainless steel cylindrical components: optimisation,

microstructure and mechanical properties. Proc Inst Mech

Eng B J Eng Manuf 2022; 237: 095440542211294.

16. Rosli NA, Alkahari MR, Ramli FR, et al. Parametric opti-

misation of micro plasma welding for wire arc additive

manufacturing by response surface methodology. Manuf

Technol 2022; 22: 59–70.

17. Koli Y, Arora S, Ahmad S, et al. Investigations and multi-

response optimization of wire arc additive manufacturing

cold metal transfer process parameters for fabrication

of SS308L samples. J Mater Eng Perform 2023; 32:

2463–2475.

18. Xia Y, Peng M, Teng H, et al. Multi-properties optimization

of welding parameters of wire arc additive manufacture in

dissimilar joint of iron-based alloy and nickel-based super-

alloy using grey-based Taguchi method. Proc Inst Mech

Eng C J Mech Eng Sci 2021; 235: 6984–6995

1. Leif. Welding duplex stainless steel —a review of current

recommendations. Weld World 2012; 56: 65–76.

2. Kumar P and Maji K. Experimental investigations and para-

metric effects on depositions of super Duplex stainless steel

in wire arc additive manufacturing. Proc Inst Mech Eng E

2023: 095440892311582.

3. Sales A, Kotousov A and Yin L. Design against fatigue of

super Duplex stainless steel structures fabricated by wire

arc additive manufacturing process. Metals (Basel) 2021;

11: 1965.

4. Zhang Y, Wu S and Cheng F. A specially-designed super

duplex stainless steel with balanced ferrite:austenite ratio

fabricated via ﬂux-cored wire arc additive manufacturing:

microstructure evolution, mechanical properties and corro-

sion resistance. Mater Sci Eng A2022; 854: 143809.

5. Horgar A, Fostervoll H, Nyhus B, et al. Additive manufac-

turing using WAAM with AA5183 wire. J Mater Process

Technol 2018; 259: 68–74.

6. Köhler M, Sun L, Hensel J, et al. Comparative study of

deposition patterns for DED-arc additive manufacturing of

Al-4046.Mater Des 2021; 210: 110122.

7. Motwani A, Kumar A, Talekar A, et al. Process parameters

optimization for cold metal transfer-deposited IN625 single-

layer bead features by entropy weightage-assisted grey-

based Taguchi analysis. Proc Inst Mech Eng E 2023:

095440892211501.

8. Koppu AK, Motwani A, Lautre NK, et al. Performance

evaluation of interfacial characteristics between cold metal

transfer-wire arc additive manufactured SS308LSi and

wrought SS304L with controlled and uncontrolled inter-

layer temperature. Proc Inst Mech Eng E, Epub ahead of

print 4 September 2023. doi: 10.1177/09544089231199223.

9. Lee SH. CMT-based wire arc additive manufacturing using

316L stainless steel: effect of heat accumulation on the

multi-layer deposits. Metals (Basel) 2020; 10: 278.

10. Pickin CG, Williams SW and Lunt M. Characterisation of

the cold metal transfer (CMT) process and its application

for low dilution cladding. J Mater Process Technol 2011;

211: 496–502.

11. Joshi GR, Badheka VJ, Darji RS, et al. The joining of

copper to stainless steel by solid-state welding processes:

a review. Materials (Basel) 2022; 15: 7234.

12. Khuri AI and Mukhopadhyay S. Response surface method-

ology. WIRES Comput Stat 2010; 2: 128–149.

13. Chelladurai SJS, Murugan K, Ray AP, et al. Optimization of

process parameters using response surface methodology:

a review. Mater Today Proc 2021; 37: 1301–1304.

14. Zhang Z, Yan J, Lu X, et al. Optimization of porosity and

surface roughness of CMT-P wire arc additive manufactur-

ing of AA2024 using response surface methodology and

NSGA-II.J Mater Res Technol 2023; 24: 6923–6941.

15. Prasanna Nagasai B, Malarvizhi S and Balasubramanian V.

A study on wire arc additive manufacturing of 308L austen-

itic stainless steel cylindrical components: optimisation,

microstructure and mechanical properties. Proc Inst Mech

Eng B J Eng Manuf 2022; 237: 095440542211294.

16. Rosli NA, Alkahari MR, Ramli FR, et al. Parametric opti-

misation of micro plasma welding for wire arc additive

manufacturing by response surface methodology. Manuf

Technol 2022; 22: 59–70.

17. Koli Y, Arora S, Ahmad S, et al. Investigations and multi-

response optimization of wire arc additive manufacturing

cold metal transfer process parameters for fabrication

of SS308L samples. J Mater Eng Perform 2023; 32:

2463–2475.

18. Xia Y, Peng M, Teng H, et al. Multi-properties optimization

of welding parameters of wire arc additive manufacture in

dissimilar joint of iron-based alloy and nickel-based super-

alloy using grey-based Taguchi method. Proc Inst Mech

Eng C J Mech Eng Sci 2021; 235: 6984–6995

1. Leif. Welding duplex stainless steel —a review of current

recommendations. Weld World 2012; 56: 65–76.

2. Kumar P and Maji K. Experimental investigations and para-

metric effects on depositions of super Duplex stainless steel

in wire arc additive manufacturing. Proc Inst Mech Eng E

2023: 095440892311582.

3. Sales A, Kotousov A and Yin L. Design against fatigue of

super Duplex stainless steel structures fabricated by wire

arc additive manufacturing process. Metals (Basel) 2021;

11: 1965.

4. Zhang Y, Wu S and Cheng F. A specially-designed super

duplex stainless steel with balanced ferrite:austenite ratio

fabricated via ﬂux-cored wire arc additive manufacturing:

microstructure evolution, mechanical properties and corro-

sion resistance. Mater Sci Eng A2022; 854: 143809.

5. Horgar A, Fostervoll H, Nyhus B, et al. Additive manufac-

turing using WAAM with AA5183 wire. J Mater Process

Technol 2018; 259: 68–74.

6. Köhler M, Sun L, Hensel J, et al. Comparative study of

deposition patterns for DED-arc additive manufacturing of

Al-4046.Mater Des 2021; 210: 110122.

7. Motwani A, Kumar A, Talekar A, et al. Process parameters

optimization for cold metal transfer-deposited IN625 single-

layer bead features by entropy weightage-assisted grey-

based Taguchi analysis. Proc Inst Mech Eng E 2023:

095440892211501.

8. Koppu AK, Motwani A, Lautre NK, et al. Performance

evaluation of interfacial characteristics between cold metal

transfer-wire arc additive manufactured SS308LSi and

wrought SS304L with controlled and uncontrolled inter-

layer temperature. Proc Inst Mech Eng E, Epub ahead of

print 4 September 2023. doi: 10.1177/09544089231199223.

9. Lee SH. CMT-based wire arc additive manufacturing using

316L stainless steel: effect of heat accumulation on the

multi-layer deposits. Metals (Basel) 2020; 10: 278.

10. Pickin CG, Williams SW and Lunt M. Characterisation of

the cold metal transfer (CMT) process and its application

for low dilution cladding. J Mater Process Technol 2011;

211: 496–502.

11. Joshi GR, Badheka VJ, Darji RS, et al. The joining of

copper to stainless steel by solid-state welding processes:

a review. Materials (Basel) 2022; 15: 7234.

12. Khuri AI and Mukhopadhyay S. Response surface method-

ology. WIRES Comput Stat 2010; 2: 128–149.

13. Chelladurai SJS, Murugan K, Ray AP, et al. Optimization of

process parameters using response surface methodology:

a review. Mater Today Proc 2021; 37: 1301–1304.

14. Zhang Z, Yan J, Lu X, et al. Optimization of porosity and

surface roughness of CMT-P wire arc additive manufactur-

ing of AA2024 using response surface methodology and

NSGA-II.J Mater Res Technol 2023; 24: 6923–6941.

15. Prasanna Nagasai B, Malarvizhi S and Balasubramanian V.

A study on wire arc additive manufacturing of 308L austen-

itic stainless steel cylindrical components: optimisation,

microstructure and mechanical properties. Proc Inst Mech

Eng B J Eng Manuf 2022; 237: 095440542211294.

16. Rosli NA, Alkahari MR, Ramli FR, et al. Parametric opti-

misation of micro plasma welding for wire arc additive

manufacturing by response surface methodology. Manuf

Technol 2022; 22: 59–70.

17. Koli Y, Arora S, Ahmad S, et al. Investigations and multi-

response optimization of wire arc additive manufacturing

cold metal transfer process parameters for fabrication

of SS308L samples. J Mater Eng Perform 2023; 32:

2463–2475.

18. Xia Y, Peng M, Teng H, et al. Multi-properties optimization

of welding parameters of wire arc additive manufacture in

dissimilar joint of iron-based alloy and nickel-based super-

alloy using grey-based Taguchi method. Proc Inst Mech

Eng C J Mech Eng Sci 2021; 235: 6984–6995