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Comparative Study on EDM Wire Cutting and CO_2 Laser Cutting for High-Precision Stainless Steel Sheet Processing

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ABSTRACT

CO_2 laser cutting and electrical discharge machining (EDM) wire cutting are two advanced thermal energy-based methods widely utilized for precision profile cutting tasks. This study conducts a comprehensive experimental analysis of these techniques, focusing on their performance when cutting stainless steel grades AISI 316L and 304. The research evaluates key process parameters influencing the cut quality, aiming to achieve minimal surface roughness. Additionally, the surface morphologies resulting from both methods are thoroughly examined. By analyzing the cutting performance and tracking the outcomes for both techniques, the study identifies the most efficient cutting technology for these materials. Using a multi-objective optimization approach based on Genetic Algorithms, the study demonstrates a significant enhancement in surface roughness. The percentages of deviations for AISI 316 Stainless steel for 1.5, 2, and 2.5 mm thickness for CO_2 laser cut and EDM wire cut surfaces are 24.8%, 21.59%, and 35.61%, respectively, and also that The percentages of deviations for AISI 304 Stainless steel for 1.5, 2, and 2.5 mm thickness for CO_2 laser cut and EDM wire cut surfaces are 36.86%, 27.88%, and 22.96%, respectively. The optimized process achieves a superior surface roughness of cutting quality. These findings offer valuable insights into selecting the appropriate cutting method and parameters for achieving high-precision results in industrial applications.

1 | Introduction

Wire electrical discharge machining (WEDM) is a special form of the non-traditional electrical discharge machining (EDM) process, whereas the electrode is a continuously traveling electrically conductive wire [1]. The past works indicate that extensive research has been carried out on the effect of various machining parameters on MRR, Ra, cutting speed, wire rupture, and wire craters [2]. The effect of the duration of the spark on-time and the ratio of the spark on-time, two important parameters of the EDM process, on the material removal rate and surface integrity of four types of advanced materials: highly porous foams, wire bond diamond milling wheels, and emission bipolar plates, was investigated in a previous study on the Wire EDM cutting process [3]. To evaluate the mechanical characteristics of AA6061-wt.5% B4Cp metal matrix composites in EDM, various machining factors are considered: current, pulses on time, and pulses off time [4]. The developed mathematical model can be used by the manufacturers while selecting the machining parameters to consider for the WEDC machining process to improve the productivity of the machining process [5]. To consider Electrode wear rate, Material removal rate, and wire feed for machining using Taguchi's orthogonal array, S/N Ratio, and Desirability Function Approach to improve productivity [6]. Learning more about Machining titanium metal sheet with a pulsed laser is a difficult thermal process. The impacts of various laser cutting conditions on such quality characteristics as HAZ layer, surface shape, and chemical resistance are investigated using Nd: YAG pulsed laser cutting of titanium alloy sheet [7–9]. The smoothest surface for mild steel cutting edges is made at intermediary speeds, which are much slower than the maximum cutting speed. Because the fluidity of the melt is quite high, the surface smoothness is increased at low rpm [10]. With an increase in cutting speeds, the cutting edge is abrasive due to the cutting front being larger [11]. Important process parameters like pulse on time, spark gap voltage, and pulse current have a remarkable effect on the output parameters of Si_3N_4-TiN material, and applied optimization techniques are using TOPSIS and GRA comparative analysis. The TOPSIS technique results yielded acquiring results [12]. TiN/AlCrN coated material evolves the surface integrity and rate of material removal during the EDM process using optimized techniques. The Taguchi method indicates that the solution is pulse time will dominantly affect surface roughness. Also, the gap current is a secondary factor for the surface roughness [13]. Earlier researchers only concentrated on optimizing the process parameters for both EDM Wire cut and CO_2 laser cut. EDM processed super alloy, which is a machined component, maintains the surface roughness at 4.50–7.36 μm at the defined peak current, which is in the value of 6–10 A from that analysis of super alloy, the peak current will influence the machining surfaces of SCT and DCT processes [14] if the current increases, wear loss occurs in a positive way, and negatively, it gives average surface roughness.

The minimum quantity lubrication (MQL) and Al_2O_3-added MQL technologies performed in the hard turning process in comparison to dry cutting. Experiments on surface roughness, cutting temperature, and tool wear were conducted in this context. The nano-MQL method improved Ra by an average of 8.51% and a maximum of 27% when compared to the MQL method, and by an average of 21.49% and a maximum of 31.8% when compared to dry machining under the same experimental conditions with the cutting tool coded AB2010. When compared to dry machining, the MQL technique improved surface roughness by an average of 13.97% and a maximum of 19.48% [15]. Consequently, it was found that the addition of 0.5 wt% nano-Al_2O_3 to the vegetable-based cutting fluid used in the MQL procedure produced noticeably higher outcomes in terms of cutting temperature values and surface roughness. The greater usage of the nano-MQL approach in machining techniques will be more effective in terms of sustainable manufacturing because of the advantages it offers over MQL and hard dry machining techniques [16]. All output parameters generally rose as the feed rate increased. When a 0.8 mm cutting nose radius was used to process 17-4 PH stainless steel, the lowest surface roughness values were recorded. Under all test settings, the 0.8 mm cutting nose radius trials had surface roughness values that were, on average, 47.48% lower than the 0.4 mm cutting nose radius experiments. To achieve a high surface quality, this martensitic stainless steel should be machined at a medium feed rate and cutting speed. Surface roughness is also significantly influenced by the cutting nose radius.

In summary, the foremost objective of the present research work is to concentrate on surface morphologies analysis of both cutting processes on AISI316L and 304L stainless steel sheets in different thicknesses considered. To obtain the application of GA analysis and CO_2 laser cutting and WEDM processes.

2 | Experimental Work

2.1 | Materials and Methods

The work piece material is prepared and machined using wire-EDM and CO_2 laser as square-shaped samples of size 10 × 10 mm with different thicknesses like 1.5, 2.0, and 2.5 mm in Figure 1c). The materials used are austenitic grades of AISI 316 L and 304 L stainless steel.

2.1.1 | Methodology

Experimental studies on the effects of the various process parameters such as Laser power, cutting speed, and Assist gas pressure on cut surface quality for AISI 304 and AISI 316L materials with various thicknesses [17]. The base material hardness values is 175BHN for 316L and 201BHN for 304 stainless steel.

Optimization routine is applied using Genetic Algorithm to find out the optimal cutting setting that would enhance the quality for AISI 304, 316L austenitic stainless-steel sheets for different thicknesses. Cut surface characterization studies are carried out for CO_2 laser cutting, and the same is compared with wire EDM surface to ascertain the quality of the laser cut.

2.2 | EDM and CO_2 Laser Process

This work based on previous experimental work and expertises available from the optimum Wire EDM parameters are selected [18]. A molybdenum wire with a diameter of 0.18 mm is used as an electrode to erode the work piece of AISI 316L and 304 materials. Figure 1a,b are two processes of WEDM and CO_2 laser cutting, the surface finish of the work item is assessed using the accompanying several measurement tools. In this experiment, the arithmetic mean roughness was used as a surface finish metric to determine surface properties (Ra). A Mitutoyo Surf test (SJ-210) was used to assess machined surfaces roughness, with a cut-off length of 0.3 mm and an assessment length of 4 mm. Each Ra measurement was made three times, with the mean determined. The surface morphology of CO_2 Laser cut and WEDM surfaces is investigated using a SEM (VEGA3-SB TESCAN).

3 | Analysis and Discussion of Results

3.1 | Combined Objective Function for AISI 304 Stainless Steel Sheet Straight Profile

The Equation (1) defines a mixed optimal solution of top, bottom kerf, and surface finish in which all answers have the same weight

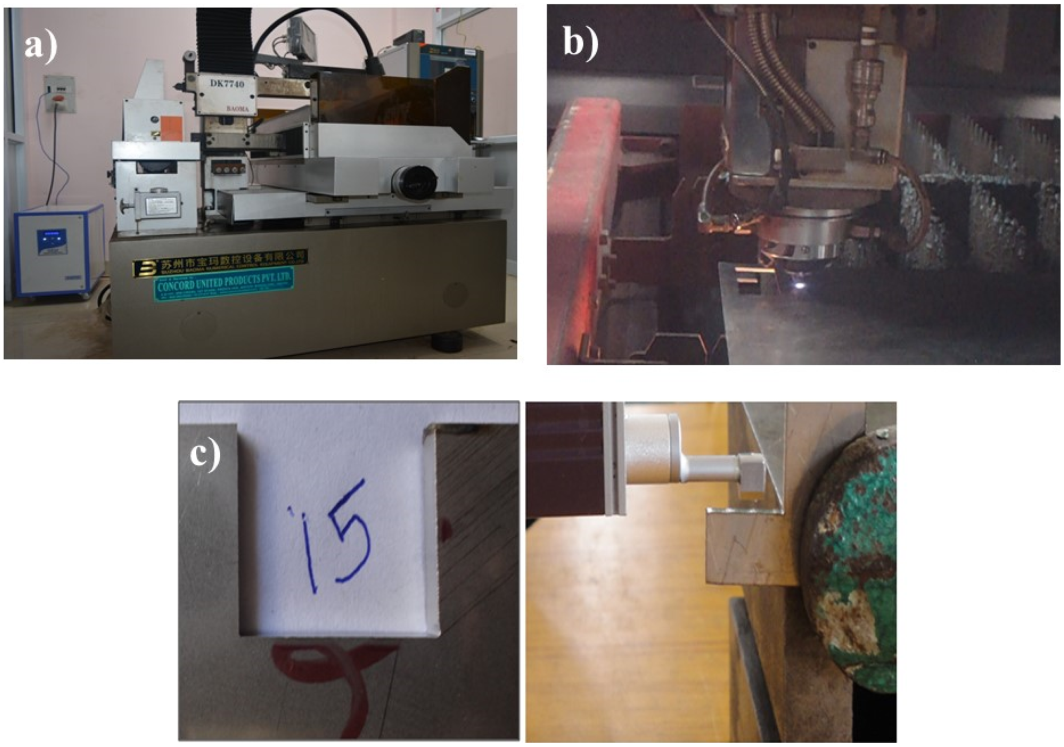


FIGURE 1 | (a) Actual photograph of experimentation on CONCORD wire EDM, model no: DK-7740 with a CNC control system, (b) experimental setup for CO_2 Laser Cutting Machine, (c) prepared and cut measurement samples of size 10 × 10 mm.

age of 0.253. The output result of the genetic algorithm software is shown in Figures 4–8, and 10. The algorithm was created using Microsoft C++ software.

$$\min(cof) = 0.25 \times \frac{tkw}{\min(tkw)} + 0.25 \times \frac{bkw}{\min(bkw)} + 0.25 \times \frac{kt}{\min(kt)} + 0.25 \times \frac{Ra}{\min(Ra)} \ldots. \quad (1)$$

Figures 2–4 shows the Genetic Algorithm for AISI 304 SS Sheet for straight profile for the responses are kerf dimensions and Ra; cumulative absolute function achieved for 1.5, 2-, and 2.5 mm thicknesses is 3.403, 3.292, and 3.554, correspondingly, for the 204th, 226th, and 22nd iterations from the total analyzed iteration.

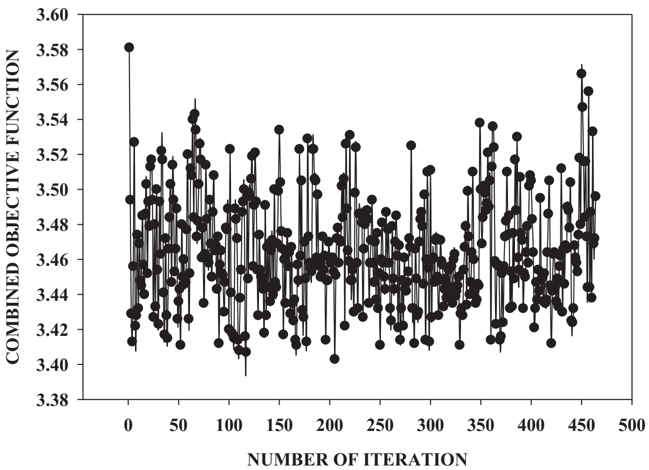


FIGURE 2 | Genetic algorithms result for AISI 304 1.5 mm thickness straight profile (combined function vs. number of iteration).

3.2 | Combined Objective Function for AISI 316 L SS Sheet Straight Profile

Figures 5–7 show the GA output result for AISI 316L SS sheet for straight profile for output parameters, that is, kerf dimensions and Ra. The results show 250th, 94th and 366th iteration give the optimum values. The conjunctive neutral value obtained is 2.936, 3.406, and 3.489 for 1.5, 2, and 2.5 mm thicknesses.

3.3 | Microstructure Analysis of AISI 316L & AISI 304 Materials

The test materials used in the cutting experiments are austenitic stainless steel AISI 316 L and AISI 304sheets. This type of stainless steel is dominant in the market. It is characterized by its high content of austenite-formers, especially nickel. The microstructure of test materials in the as-received condition using optical microscopy with an image analysis system at 40× magnification is depicted and stainless steel—aqua regia etchant are used [19]. It is evident from Figures 8 and 9 that the normalized microstructure consists of austenitic grains and twins, and there is no formation of carbides.

Figure 10 shows that SS316L chemical composition nickel content 6.6%and iron content 71.71% based on that Edx analysis nickel content 0.3% increase when compared to 304 material.

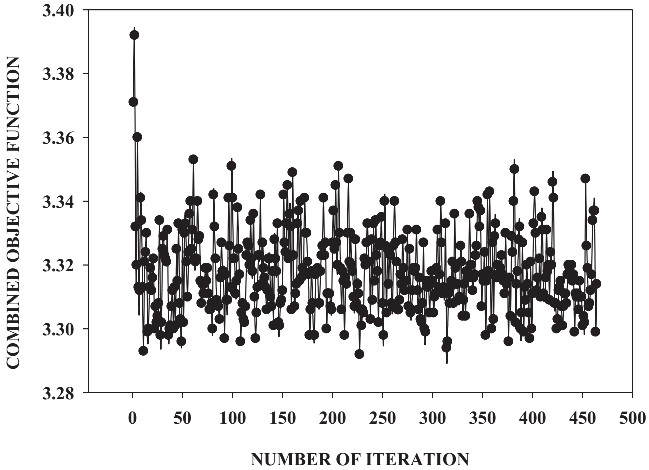


FIGURE 3 | Genetic algorithm of AISI 304 2 mm thickness for straight profile (combined function vs. number of iteration).

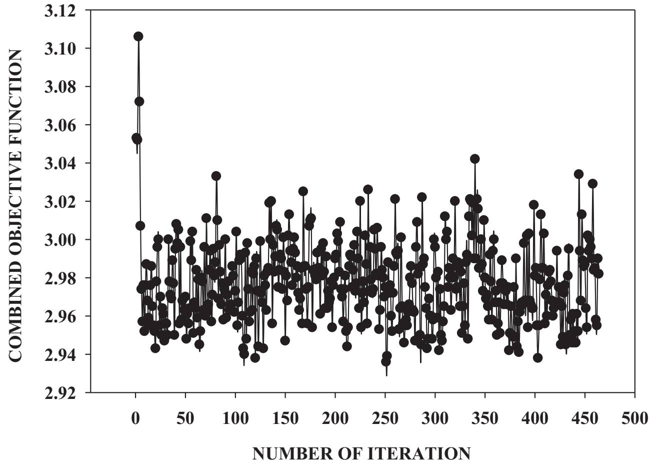


FIGURE 6 | Genetic algorithm of AISI 316L 2 mm thickness for straight profile (combined function vs. number of iteration).

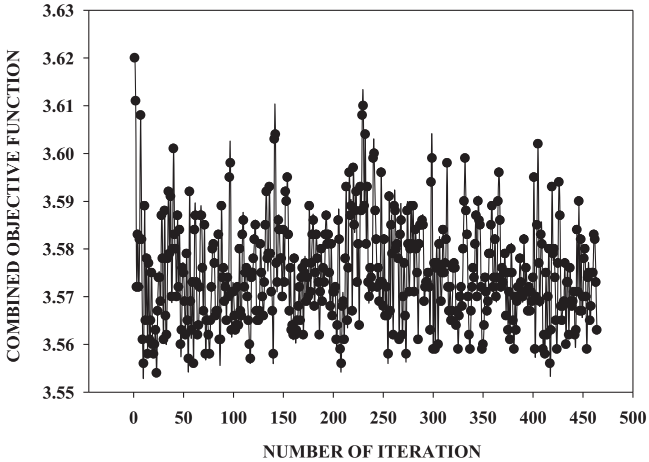


FIGURE 4 | Genetic algorithm of AISI 304 2.5 mm thickness for straight profile (combined function vs. number of iteration).

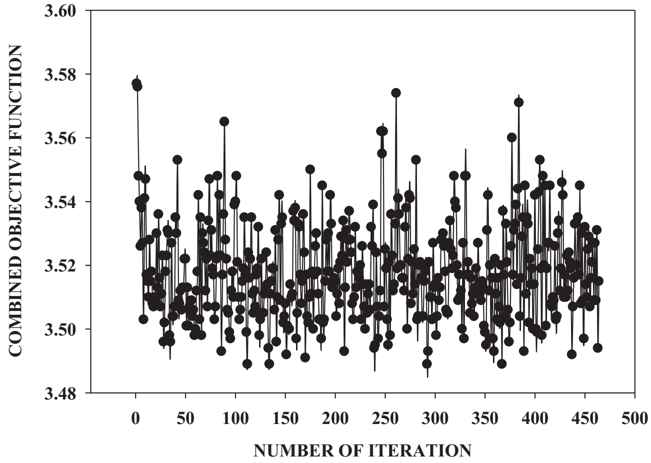


FIGURE 7 | Genetic algorithm of AISI 316L 2.5 mm thickness for straight profile (combined function vs. number of iteration).

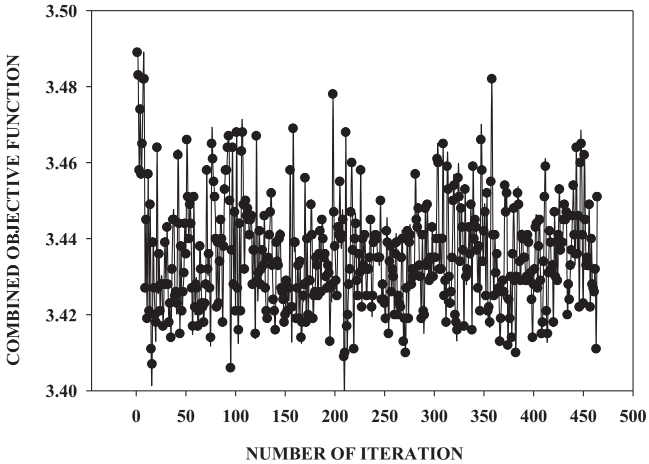


FIGURE 5 | Genetic algorithm of AISI 316L 1.5 mm thickness for straight profile (combined function vs. number of iteration).

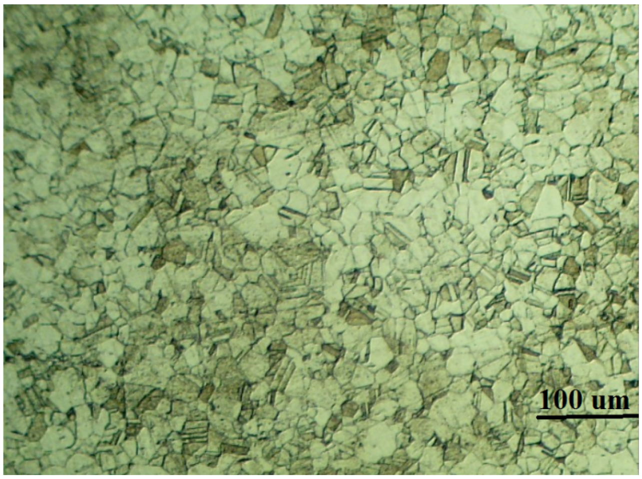


FIGURE 8 | Base materials microstructure of AISI 316L.

Figure 11 shows the EDx Analysis, which shows iron content 74.75% and chromium content 18.94% also the nickel content 6.31%, and carbon content 2.2% based on this edx analysis, confirm with the composition of SS304.

3.4 | Laser Cut and EDM Wire Cut Surfaces of Austenitic Stainless Steel AISI 316L Sheets

The surface morphologies of the WEDM and laser cut workpieces for three different thicknesses of AISI 304 stainless steel sheet are presented in Figures 12 and 13. It is observed that the wire EDMed workpiece is affected. It can be seen from Figure 12a,b the laser cutting edges have better surface quality compared to that of wire-EDM cutting. It is also seen that Figure 12b has a high surface quality with low surface roughness values of 1.348 μm as against the EDM wire cut surface roughness of 2.035 μm that is recorded in Figure 12a.

The high surface quality achieved by the laser cutting can be attributed to the laser beam being properly focused on the bottom surface of the sheet metal, which gives pronounced striations on the laser cut surface; this in turn gives the appearance of a finer edge, and the nitrogen blows away the molten material for better surface quality. The surface roughness values are recorded for all the laser cut and wire-EDMed surfaces, and the values are listed in Table 1. According to the results of the experiments, it shows that the surface roughness in the laser cut surface increases when the workpiece thickness increases. This is because, as the thickness of the sheet metal increases, striations are noticed along with the top edge of the sheet metal, as shown in Figures 13 and 14 and towards the middle to lower section, these striations become much smoother. The upper portion of the sheet metal absorbs the laser energy, resulting in blunt striations, while the lower smoother edge is the consequence of molten material flow ejection generated by the assist gas blow effect [20]. In Figure 13a after wire EDM of AISI 316 L stainless steel, the surface morphology seen in the SEM image shows typical crater forms brought on by electrical discharges during cutting. The uneven loss of material is shown by the random distribution and size variation of these craters. Because EDM melts and solidifies quickly, a thin, resolidified recast layer is visible. Moreover, microcracks that are probably the result of heat stress are visible, spreading from some crater rims. There are molten globules and tiny debris particles all over the surface, which could indicate inadequate flushing during cutting. These formations are compatible with the material deposition and thermal erosion processes associated with EDM wire cut. The rough surface of the upper edge of the thick sheet metal when cut with CW is typically the result of many differing variables, resulting in high Ra. However, there is not much variation in the surface roughness of the wire EDMed surface when the workpiece thickness is enhanced from 1.5 to 2.5 mm. The SEM images envisage that no heat-affected zone is occurring in all the laser cut and wire EDMed edges.

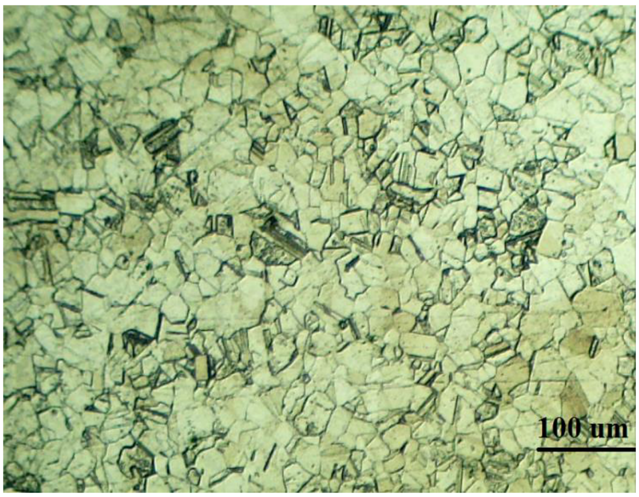


FIGURE 9 | Base materials microstructure of AISI 304L.

3.5 | Laser Cut and EDM Wire Cut Surfaces of Austenitic Stainless Steel AISI 304 Sheets

SEM morphology of AISI 304 stainless steel work piece in laser cutting and wire-EDM. The surface morphologies of the wire EDMed and laser cut work pieces for three different thicknesses of AISI 304 stainless steel sheets are presented in Figures 15–17, and the cavities are detected on the wire EDMed work piece. Figure 15a,b demonstrate that, compared to wire-EDM, the laser cut produced a superior surface quality on the work piece. Figure 15b likewise shows a superior surface quality, with surface roughness values of 1.348 μm compared to 2.035 μm in Figure 13a.

The superior surface quality attained by laser cutting is due to the laser beam being appropriately focused on the sheet metal's bottom surface, which results in prominent striations on the laser

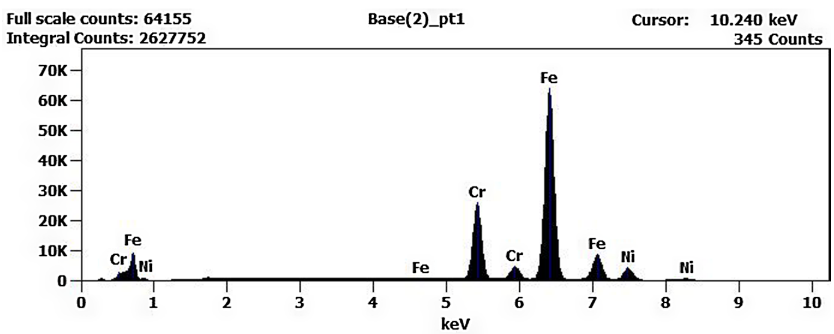


FIGURE 10 | Base materials EDX analysis of AISI 316L.

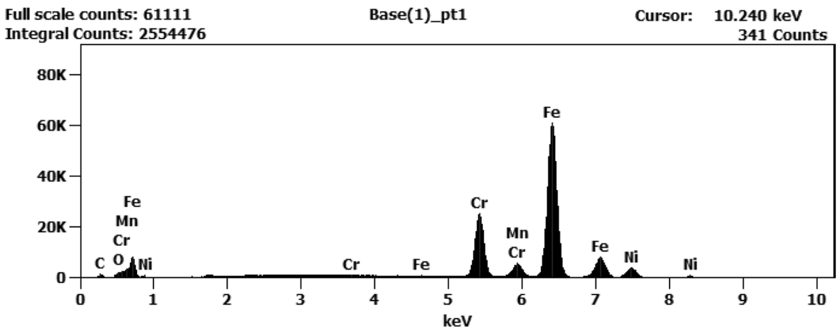


FIGURE 11 | Base materials EdX analysis of AISI 304.

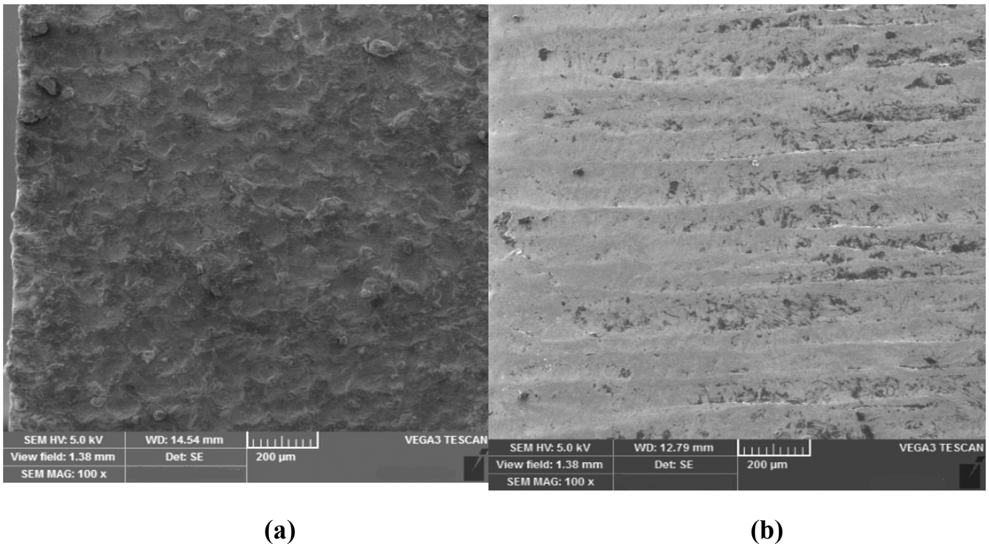


FIGURE 12 | SEM image of AISI 316L cut surface (a) EDM wire cut and (b) laser cut for 1.5 mm thick sheet.

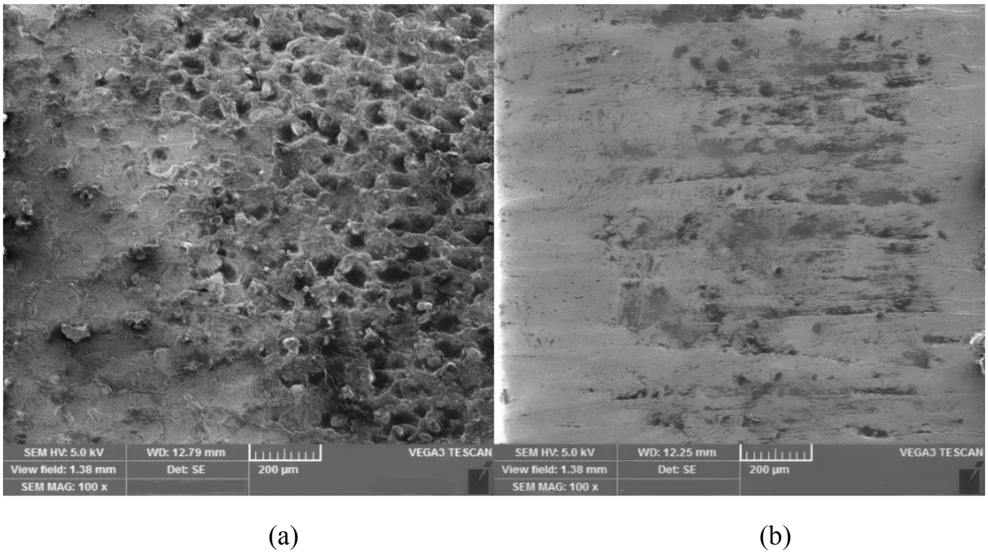
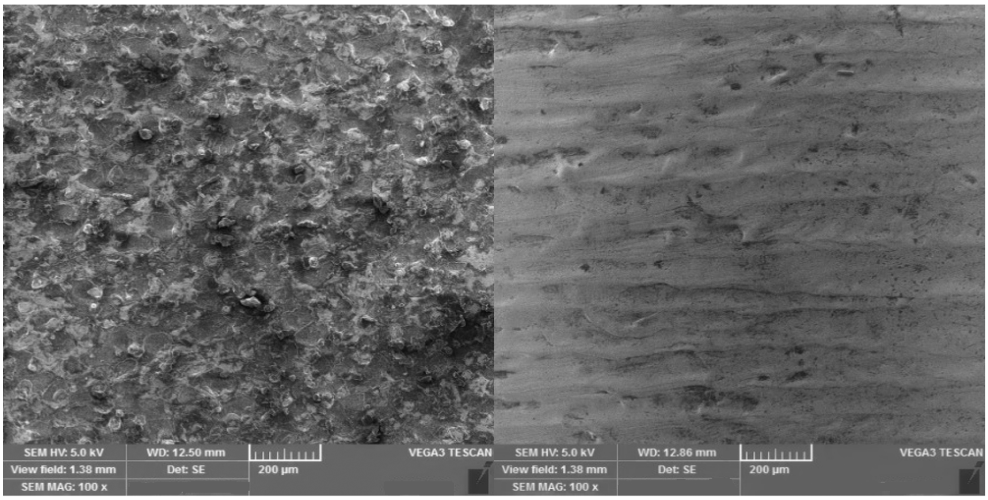


FIGURE 13 | SEM image of AISI 316L cut surface (a) EDM wire cut and (b) laser cut for 2.0 mm thick sheet.

cut surface. Furthermore, the flushing action of dielectric fluid between the workpiece and the electrode has no influence on the attachment to the electrode-workpiece surface after consecutive erosion [21]. The surface roughness values are recorded for all the laser cut and wire-EDMed surfaces, and the values are listed in Table 2 the surface roughness in laser cut surface increases when the workpiece thickness increases. This is because the thickness of the sheet metal increases; striations are noticed along with

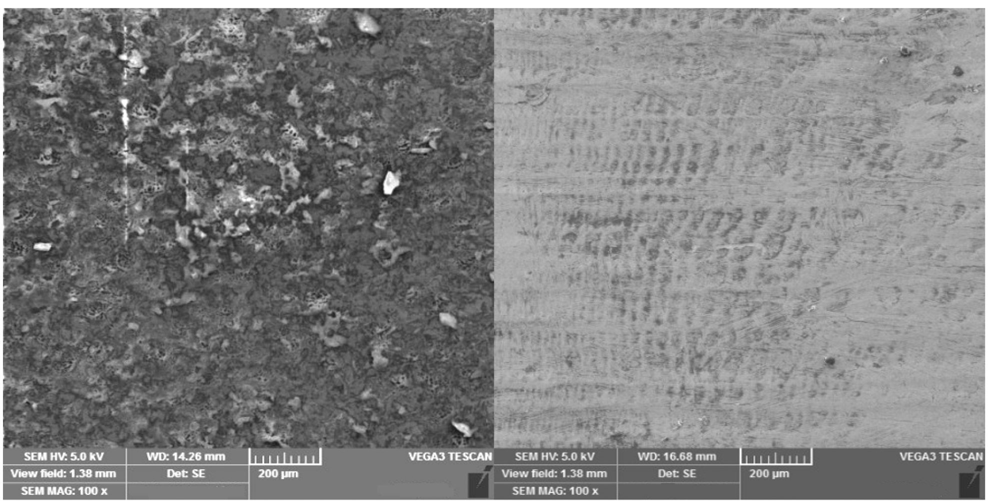
TABLE 1 | Surface roughness's of Laser cut and wire EDM of AISI 316L stainless steel sheet.

Sl. No	Thickness	Responses	GA predicted value for CO_2 laser cutting	Experimental predicted value for CO_2 laser cutting	Experimental predicted value for WEDM	% of Deviation
1	1.5	Surface roughness (μm)	1.5943	1.648	2.242	26.494
				1.683	2.201	23.534
				1.654	2.192	24.543
Average value				1.661	2.211	24.868
2	2	Surface roughness (μm)	1.8247	1.913	2.453	22.013
				1.904	2.396	20.534
				1.892	2.432	22.203
Average value				1.903	2.427	21.590
3	2.5	Surface roughness (μm)	1.8928	1.948	2.592	34.490
				1.987	2.612	35.987
				1.959	2.642	36.336
Average value				1.964	2.615	35.610



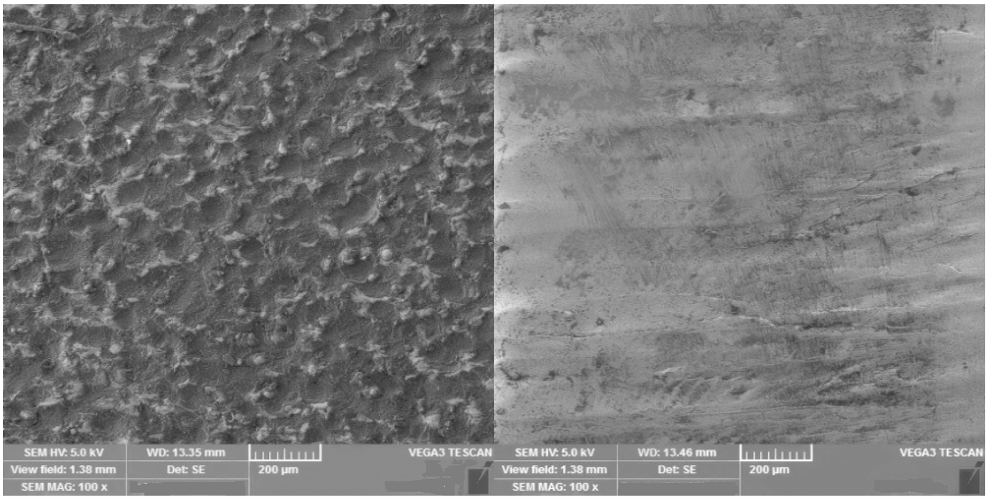
(a) (b)

FIGURE 14 | SEM image of AISI 316 L cut surface (a) EDM wire cut and (b) laser cut for 2.5 mm thick sheet.



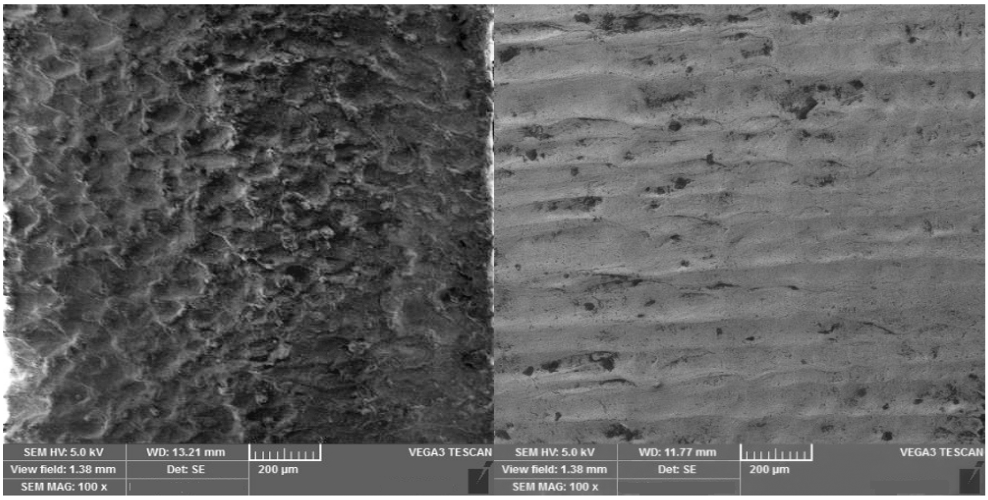
(a) **(b)**

FIGURE 15 | SEM image of AISI 304 cut surface (a) EDM wire cut and (b) laser cut for 1.5 mm thick sheet.



(a) **(b)**

FIGURE 16 | SEM image of AISI 304 cut surface (a) EDM wire cut and (b) laser cut for 2.0 mm thick sheet.



(a) **(b)**

FIGURE 17 | SEM image of AISI 304 cut surface (a) EDM wire cut and (b) laser cut for 2.5 mm thick sheet.

the top edge of the sheet metal, as shown in Figures 16 and 17 and towards the middle to lower section, these striations become much smoother. The upper portion of the sheet metal absorbs the laser energy, resulting in blunt striations, while the lower smoother edge is the consequence of molten material flow ejection generated by the assist gas blow effect [15]. The surface roughness of the upper edge of the thick sheet metal when cut with CW is typically the result of many differing variables, resulting in high surface roughness. However, there is not much variation in the surface roughness of the wire-EDMed surface when the workpiece thickness is increased from 1.5 to 2.5 mm. The SEM images envisage that no heat-affected zone is occurring in all the laser cut and wire-EDMed edges [22–24].

Figure 18 shows from the genetic algorithm we observed that the lowest thickness 1.5 mm AISI304L materials which gives the lowest surface roughness value, we confirmed that lower values of surface roughness are suited for the process.

4 | Conclusions

The surface quality, morphology, and roughness of AISI 304 & 316L, austenitic stainless steel, and during laser cutting and wire-EDM are experimentally investigated and analyzed in the present work. The austenitic stainless steel results inferred that the laser cut achieved high cutting-edge surface quality of the workpiece when compared to that of WEDM cutting. Further, the roughness of the 316L steel cutting edge surface is higher than the surface roughness of the 304 steel cutting edge surfaces with an identical thickness using the CW-series, CO_2 laser cutting system and wire-EDM.

The results of GA, which predicts surface roughness values of 1.318, 1.704, and 1.871 µm for AISI 304 stainless steel and 1.594, 1.824, and 1.89 µm for AISI 316 stainless steel, were compared to CO_2 laser cutting and EDM wire cut under all conditions of different material thicknesses.

TABLE 2 | Surface roughness of laser cut and wires EDM of AISI 304 stainless steel sheet.

Sl. No	Thickness	Responses	GA predicted value for CO_2 laser cutting	Experimental predicted value for CO_2 laser cutting	Experimental predicted value for WEDM	% of Deviation
1	1.5	Surface roughness (μm)	1.318	1.325	2.014	34.210
				1.362	2.162	37.002
				1.358	2.231	39.130
Average value				1.348	2.035	36.865
2	2	Surface roughness (μm)	1.7014	1.764	2.456	28.175
				1.792	2.543	29.532
				1.803	2.432	25.863
Average value				1.786	2.477	27.883
3	2.5	Surface roughness (μm)	1.871	1.959	2.542	22.934
				1.981	2.612	24.157
				1.951	2.493	21.740
Average value				1.963	2.549	22.963

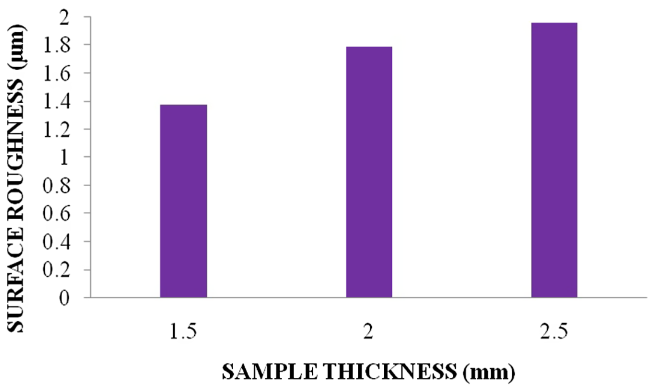


FIGURE 18 | Surface roughness of different thicknesses (1.5, 2, and 2.5 mm) using genetic algorithm output.

The CO_2 laser cutting surface performs better than the EDM wire cut, with AISI 316 stainless steel measuring 1.661, 1.903, and 1.964 μm, and 1.348, 1.786, and 1.963 μm for AISI 304 stainless steel.

The CO_2 laser cutting method exhibits significantly better surface integrity and significantly less surface roughness than the wire EDM method. CO_2 laser cutting is now a more beneficial and effective machining method due to its enhanced performance, especially in industrial settings where high precision, low heat damage, and superior surface smoothness are essential for the quality of the finished product.

Author Contributions

A. Parthiban: conceptualization, visualization, software, resources, writing – review and editing. **K. Ananthakumar:** investigation, methodology, validation, software, formal analysis, data curation, writing – review and editing. **S. Ajith Arul Daniel:** conceptualization, investigation, writing – review and editing, formal analysis, software, supervision, resources. **S. Sivaganesan:** writing – review and editing, visualization, investigation, validation, software, formal analysis, supervision, resources. **T. Sathish:** conceptualization, investigation, funding acquisition, writing – original draft, writing – review and editing, visualization, validation, methodology, software, formal analysis, project administration, resources, supervision, data curation. **Jayant Giri:** conceptualization, funding acquisition, visualization, writing – review and editing, formal analysis, supervision. **A. Johnson Santhosh:** conceptualization, validation, writing – review and editing, software, supervision, project administration, data curation, investigation, writing – original draft. **Ahmad O. Hourani:** conceptualization, writing – review and editing, methodology, formal analysis, resources.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

1. V. R. Gondalia and A. K. Sharma, "Parametric Investigation and Optimization of CO_2 Laser Cutting Process Used for Cutting Hardox-400 Materials," *International Journal of Science and Engineering Applications* 2, no. 6 (2013): 123–129.

2. V. Singh and S. K. Pradhan, "Optimization of EDM Process Parameters: A Review," *International Journal of Emerging Technology and Advanced Engineering* 4, no. 3 (2014): 345–355.

3. A. S. Viswanathana, D. Rajarajana, P. Harish Kumar, and A. K. Nathb, "Laser Irradiation of AISI 316L Stainless Steel Coated With Si_3N_4 and Ti," *Optics & Laser Technology* 39 (2007): 1504–1513.

4. H. Wahab, J. Gröninger, K. Dickmann, et al., "Optimization of Laser Cutting Quality With Design of Experiments," *Laser Technik Journal* 11, no. 5 (2014): 27–31.

5. C. Wandera, "Laser Cutting of Austenitic Stainless Steel With a High-Quality Laser Beam, Master's Thesis, Lappeenranta University of Technology, Finland," 2006.

6. J. Wang, "An Experimental Analysis and Optimisation of the CO_2 Laser Cutting Process for Metallic Coated Sheet Steels," *International Journal of Advanced Manufacturing Technology* 16 (2000): 334–340.

7. L. M. Wee, P. L. Crouse, and L. Li, "A Statistical Analysis of Striation Formation During Laser Cutting of Ceramics," *International Journal of Advanced Manufacturing Technology* 36 (2008): 699–706.

8. B. S. Yilbas, S. S. Akhtar, E. Bayraktar, and Z. Gasem, "Laser Cutting of Thin Aluminum and Silicon Alloy: Influence of Laser Power on Kerf Width," *Advanced Materials Research* 445 (2012): 442–447.

9. A. Parthiban, R. Ravikumar, B. Suresh Kumar, and N. Baskar, "Hybridization of Response Surface Methodology and Genetic Algorithm Optimization for CO_2 Laser Cutting Parameter on AA6061 Material," *International Journal of Engineering and Technology* 6, no. 1 (2014): 358–373.

10. B. S. Yilbas, S. Khan, K. Raza, et al., "Laser Cutting of 7050 Al Alloy Reinforced With Al_2O_3 and B_4C Composites," *International Journal of Advanced Manufacturing Technology* 50 (2010): 185–193.

11. B. S. Yilbas, "Laser Cutting of Thick Sheet Metals: Effects of Cutting Parameters on Kerf Size Variations," *Journal of Materials Processing Technology* 20I (2008): 285–290.

12. S. Baskar, D. S. Kumar, R. Dhinakaran, A. Prabhakaran, B. Arun, and M. Shanmugam, "Experimental Studies on Mechanical and Morphological Property of the Natural and SBR/BR Hybrid Rubber," *Materials Today: Proceedings* 37 (2021): 1503–1506.

13. A. Prabhakaran, K. S. Krishnan, R. Dhinakaran, S. Baskar, and V. S. Shaisundaram, "Analysis of the Efficiency of an Automotive Alternator by Replacing Mild Steel Into Aluminum as a Material for Rotor," *Materials Today: Proceedings* 37 (2021): 1269–1273.

14. F. Kara, N. Bulan, M. Akgün, and U. Köklü, "Multi-Objective Optimization of Process Parameters in Milling of 17-4 PH Stainless Steel Using Taguchi-Based Gray Relational Analysis," *Engineered Science* 26 (2023): 961.

15. E. Nas and F. Kara, "Optimization of EDM Machinability of Hastelloy C22 Super Alloys," *Machines* 10, no. 12 (2022): 1131.

16. F. Kara, "Investigation of the Effect of Al2O3 Nanoparticle-Added MQL Lubricant on Sustainable and Clean Manufacturing," *Lubricants* 12, no. 11 (2024): 39.

17. A. Parthiban, R. Ravikumar, H. Abdul Zubar, and M. Duraiselvam, "Experimental Investigation of CO_2 Laser Cutting on AISI 316L Sheet," *Journal of Scientific & Industrial Research* 73 (2014): 387–393.

18. A. M. Patel and V. Achwal, "Optimization of Parameters for WEDM Machine for Productivity Improvement," *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)* 9 (2013): 10–14.

19. P. V. Yudina, A. V. Zaitseva, O. B. Kovaleva, and E. Grigory, "Fundamental Study of CO_2- and Fiber Laser Cutting of Industrial Materials With High-Speed Visualization Technique, 8th International Conference on Photonic Technologies," (2014):1–9.

20. M. Zaied, E. Bayraktar, D. Katundi, M. Boujelbene, and I. Miraoui, "Effect of Laser Cutting Parameters on Surface Quality of Low Carbon Steel (S235)," *Journal of Achievements in Materials and Manufacturing Engineering* 54, no. 1 (2012): 128–134.

21. E. Nas and S. Uzuner, "Optimization of Laser Cutting Parameters for Improved Surface Quality in AISI 304 Stainless Steel," *Gazi Journal of Engineering Sciences* 9, no. 3 (2023): 654–662, https://doi.org/10.30855/gmbd.0705096.

22. T. V. B. Babu, N. Gobu, S. Kaliappan, and L. Natrayan, "Mechanical Fatigue and Microstructure Behaviour of Cassava Peel SiO_2 Strengthened Friction Stir Welded AA 6065-Al_2O_3 Metal Matrix Composite Joints," *Surface Review and Letters* 12, no. 2 (2025): 1–12.

23. R. Parikh, S. Parikh, K. Sharma, et al., "Experimental Investigations on the Productivity Increase of Solar Stills Utilising Hybrid Nanomaterials and Water-Cooling Techniques," *Energy Exploration & Exploitation* 4, no. 2 (2025): 1445987241308588.

24. S. Kumar, R. Jasrotia, P. Puri, et al., "A New Class of Multifunctional CoDyzFe2−zO_4 Magnetic Nanomaterials: Influence of Structural, Morphological, Optical, Magnetic, Antibacterial, and Photocatalytic Traits," *ECS Journal of Solid State Science and Technology* 13, no. 7 (2024): 77004.