International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

WEDM Process Parameters: An Overview and Analysis

Sanjeet Kumar, Kriti Srivastava, Nitesh Kumar Dixit
Department of Mechanical Engineering
Institute of Engineering and Technology, DRMLAU, Ayodhya, U.P., India
Sanjeet.auto@gmail.com

Abstract: Wire Electrical Discharge Machining (WEDM) is a non-conventional machining method that utilizes thermal electrical energy to fabricate intricate structures with precision and a polished surface finish. It is particularly suited for machining robust materials that pose challenges for conventional manufacturing due to factors like vibrations. This machining technique involves a range of process parameters and performance indicators critical to its effectiveness. Key parameters such as pulse-off-time (T_{OFF}), servo voltage (SV), pulse-on-time (T_{ON}), peak current [I], and wire tension (WT) play significant roles in determining outcomes such as surface roughness (SR), material removal rate (MRR), and Kerf width (KW). Current research trends in WEDM emphasize optimizing these parameters to enhance performance across various materials, including alloys, superalloys, and composites. Optimization techniques such as the Taguchi method, Grey Relation Analysis (GRA), and analysis of variance (ANOVA) are widely applied to refine WEDM processes. These methods help in understanding the complex interactions between process variables and material characteristics, aiming to achieve superior machining results. In conclusion, the study highlights the importance of meticulous parameter control and optimization strategies in WEDM to maximize efficiency and quality in machining operations across diverse material types. These insights contribute to advancing the capabilities and applications of WEDM in modern manufacturing settings.

Keywords: WEDM, Parameters for Enhancing Performance, Various Optimization Techniques, ANOVA.

1. Introduction:

Electrical Discharge Machining (EDM) has emerged as a superior solution for machining a wide range of materials known for their high strength, exceptional corrosion resistance, and impressive wear resistance. This method effectively addresses the challenges posed by an increasing variety of high-performance materials. Wire Electrical Discharge Machining (WEDM), a non-traditional machining technique, utilizes thermal electrical energy to manufacture intricate structures. In Wire Electrical Discharge Machining (WEDM), material is removed from a workpiece through a series of electrical sparks. This process utilizes a moving wire electrode that passes through the workpiece, controlled by a Computer-Numerically Controlled (CNC) machine [3]. Unlike conventional machining methods that physically cut material, WEDM achieves material removal through electrical spark erosion. Therefore, materials processed with WEDM must be electrically conductive. Electrical pulses in the form of Direct Current (DC) are generated between the workpiece and the wire electrode, with deionized water acting as a dielectric medium between them. While pure water is normally an insulator, tap water may contain minerals that increase its conductivity, rendering it unsuitable for WEDM applications [4]. To address this, water is passed through a resin tank to remove conductive impurities, producing deionized water. During operation, water conductivity tends to increase, prompting an automatic pump to cycle water through the resin tank when conductivity levels become too high [5,6]. Figure 1 illustrates the schematic of the WEDM process.

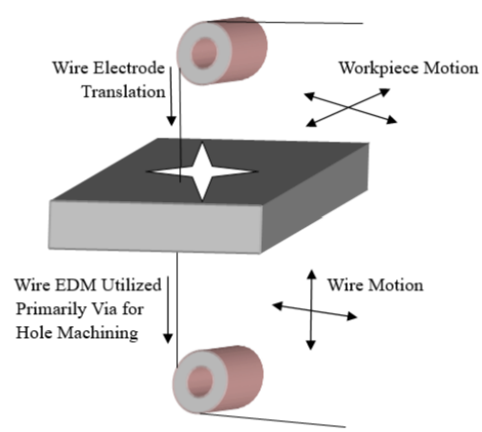

Fig. 1. Schematic of the WEDM process

2. Components of WEDM

- **Workpiece:** WEDM can machine all conductive materials effectively.
- **Tool Electrode:** The electrode in WEDM shapes the cavity to be manufactured; typically, a wire serves as the tool electrode.
- **Dielectric Fluid:** WEDM involves immersing both the workpiece and the wire electrode in a tank filled with dielectric fluid.
- **Servo System:** Controlled by signals from the gap voltage sensor system of the power supply, the servo

International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

system manages the feed of both the workpiece and the electrode to optimize Material Removal Rate (MRR).

- **Power Supply:** This unit converts Alternating Current (AC) from the main power supply into Direct Current (DC) pulses required to generate sparks between the machining gap. The DC pulse generator precisely controls current, voltage, and duration of these pulses [7].
- **Objective:** This article aims to explore how WEDM parameters such as T_{OFF} (pulse-off-time), T_{ON} (pulse-on-time), peak current (I), wire tension, and wire feed rate impact various material responses in terms of Electrode Wear (EW), surface integrity, Kerf width, and MRR [8,9].

3. WEDM Process Parameters

After conducting an extensive literature review, several key findings have emerged. The research prominently focuses on exploring WEDM processes applied to superalloys and composites. Experimental evidence consistently shows that increasing parameters such as pulse on time (T_{ON}), servo voltage (SV), and peak current (I) contribute significantly to improving surface quality. In contrast, pulse on time, wire tension, and wire feed are found to have minimal impact on material removal rate (MMR) or surface roughness (SR).

Furthermore, the majority of research efforts have concentrated on enhancing and optimizing conventional performance measures like MMR, SR, and kerf width (KW) across diverse materials. However, critical performance metrics such as dimensional deviation, hardness, and gap current have either been overlooked or insufficiently addressed in existing studies. This highlights a clear need for further exploration and investigation in these specific areas to deepen our understanding of how WEDM parameters influence these overlooked or underexplored aspects.

In conclusion, the literature review underscores the necessity of broadening the scope of investigation to encompass a more comprehensive range of performance metrics within the realm of WEDM processes. This expansion promises to enhance overall understanding and application of WEDM across various manufacturing contexts.

4. WEDM Process Response (Output)

Numerous factors impact the WEDM process, including surface roughness, kerf width, micro-hardness, and microstructure, all of which are crucial for evaluating machining precision across various industries. Achieving a balance between high production rates and maintaining acceptable quality levels hinges on selecting the optimal combination of WEDM parameters such as current, T_{ON} (pulse on time), TOFF (pulse-off time), and feed rate [15]. This strategic parameter selection is essential for maximizing efficiency without compromising on machining accuracy or component quality.

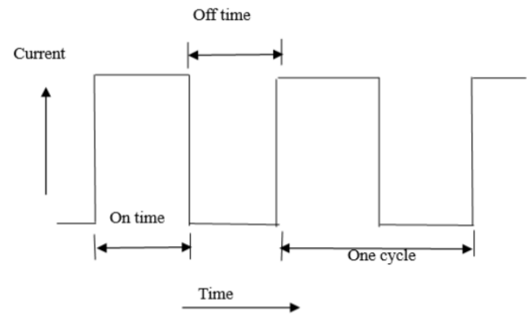

Fig. 2. Process parameters (pulse on time, pulse off time, peak current)

5. Literature Review:

The existing literature on WEDM (Wire Electrical Discharge Machining) can be categorized into three main sections focusing on Surface Roughness (SR), Kerf Width (KW), and Material Removal Rate (MRR). This classification aims to provide a structured framework for understanding the diverse configurations of WEDM parameters, their intricate interactions, and their implications for potential research avenues. By organizing research in this way, it assists researchers and practitioners in navigating the complexities of WEDM, facilitating deeper insights into the implications of parameter settings for future investigations in the field [16].

Surface roughness (SR) is a critical factor influencing surface integrity in Wire Electrical Discharge Machining (WEDM). Khan et al. [17] studied the impact of WEDM parameters on stainless steel SR, using Grey Relational Analysis (GRA) to identify optimal parameter combinations, highlighting T_{ON} as a significant influencer. Bobbili et al. [18] and Shunmuga et al. [19] also investigated SR, emphasizing parameters like T_{ON}, I, and spark voltage. Hong et al. [20] examined cutting voltage, T_{ON}, T_{OFF}, and SV, showing their significant influence on SR through variance analysis. ElBahloul et al. [21] optimized WEDM settings for low SR in AISI 304, finding increased T_{ON} and I, and decreased T_{OFF} resulted in rougher surfaces. Hema et al. [22] and Murali et al. [23] employed Taguchi methods to optimize SR by varying parameters such as T_{ON}, T_{OFF}, and wire tension. Sapit Azwan et al. [25] used ANOVA to enhance SR with nano-powder dielectric fluid, achieving a notable improvement. Mukulanand Jha et al. [26] and Kandala et al. [27] used Taguchi and Response Surface Methodology (RSM) to predict optimal SR conditions, identifying T_{ON} as crucial. Noha Naeim et al. [28] analyzed WEDM parameters on SS (304), confirming current, T_{ON}, and T_{OFF} as highly influential factors affecting SR. R. Rawat et al. [29] optimized AA6061 SR using Taguchi and GRA, pinpointing T_{ON} and peak current (I) as critical. Hammami et al. [30] evaluated WEDM on aluminum alloys, emphasizing T_{ON} and $T_{OFF's}$ impact on SR. Vinod Kumar et al. [31] and Devarasiddappa et al. [32] used Response Surface Methodology and Taguchi methods to optimize Nimonic-90 and Ti6Al4V alloy SR, respectively, showing T_{ON} and current as dominant factors influencing SR.

Protim et al. [33] identified optimal WEDM parameters (T_{ON} = 115 µs, T_{OFF} = 35 µs, SV = 40 V, WT = 5 kgf) that maximize Material Removal Rate (MRR). Pramanika et al. [34] studied the effects of wire tension, T_{ON}, and T_{OFF} on MRR, finding that longer T_{ON} and reduced T_{OFF} increase MRR significantly. Priyadarshini et al. [35] investigated T_{ON}, T_{OFF}, and SV effects on low-carbon mold steel, concluding that increasing T_{ON} indefinitely increases MRR, with optimal settings identified as T_{ON} = 120 µs, T_{OFF} = 23 µs, SV = 40 V. Chaudhary et al. [36] examined WEDM parameters (wire tension, T_{ON}, dielectric fluid) affecting material removal rate in nimonic alloy gears, highlighting dielectric fluid, T_{OFF}, wire tension, peak current, and T_{ON} as critical factors. Basavaraju et al. [37] correlated WEDM parameters (T_{ON}, T_{OFF}, Indicated Power) with MRR in Titanium Grade-7 alloy, using ANOVA to optimize for high MRR, identifying T_{ON} as most significant. Pawan Kumar et al. [38] explored multiple WEDM parameters and their impact on MRR, with optimal conditions for achieving high MRR (27.691 mm²/min) determined at T_{ON} = 110, T_{OFF} = 35, SV = 46 V, IP = 120 A. Kalyanakumar et al. [39] investigated SS304 stainless steel WEDM parameters, optimizing MRR through Grey Relation Analysis, identifying T_{ON} = 105 µs, T_{OFF} = 63 µs, IP = 210 V, and wire feed = 24 m/min as optimal conditions.

Suresh et al. [40] explored the application of WEDM for cutting AleSiCeB4C hybrid metal matrix composites, analyzing current, pulse on time, and wire feed rate to assess their impact on kerf width. Using Response Surface Methodology (RSM), they achieved a minimum kerf width of 0.271 mm at a wire feed rate of 10 mm/min and a current of 12 A. Optimal machining conditions identified by RSM included a current of 20 A, pulse on time of 108.6 µs, and a wire feed rate of 10 mm/min.

Sridhar et al. [41] investigated various parameters such as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flushing pressure in WEDM to optimize kerf width (KW) using the Grey Taguchi approach. Their experimental approach aimed to minimize kerf width by adjusting these parameters for enhanced WEDM performance.

Babasaheb Shinde et al. [42] studied the impact of servo reference voltage variations on kerf width accuracy in WEDM. They identified an optimal graphite concentration range of 3 to 5 g/liter, observing stable ceramic erosion within this range, which contributed to achieving optimum kerf width. They noted that increasing gap voltage led to a consistent increase in kerf width for each graphite concentration.

Ishfaq et al. [43] highlighted current as the most influential factor affecting KW in WEDM processes based on their study findings.

Bagal et al. [44] investigated the limitations of WEDM on kerf width in SS 304 grade, with ANOVA results indicating that pulse on time (T_{ON}) was the most significant factor influencing KW.

Muniappan et al. [45] focused on enhancing kerf width in WEDM for Aluminum hybrid composites using Zinc-coated brass wire. Their Taguchi orthogonal method experiment revealed that Pulse on Time exerted the most significant influence on kerf width, surpassing even peak current's impact.

Ablyaz et al. [46] examined wire-cut electro-discharge machining (W-EDM) of polymer composite materials, varying TON, voltage, and T_{OFF} to optimize kerf width accuracy. Their study included developing a theoretical machining model that demonstrated efficacy within an acceptable range of parameters.

Pujara et al. [47] conducted experiments to optimize process parameters (T_{ON}, T_{OFF}, peak current, and wire feed) using Taguchi L9 orthogonal array and Grey Relational Analysis (GRA) in WEDM operations. They found pulse on time and peak current to be significant factors influencing kerf width, alongside pulse off time and wire feed.

Yasir Nawaz et al. [48] applied the Taguchi method to study the influence of factors in WEDM on kerf width of DC53 die steel, emphasizing current intensity and pulse on time as crucial parameters. Optimal values identified for achieving minimal kerf width included 4 µs pulse on time, 9 µs pulse off time, 1 A peak current, and 7 m/s wire speed.

Ramesh et al. [49] analyzed kerf width in WEDM of Die Steel D3 using an orthogonal array incorporating peak current, pulse on time, and pulse off time as key machining parameters. They concluded that peak current had the most substantial impact on kerf width among the selected parameters.

Ashish Goyal et al. [50] conducted experiments on NiTi using WEDM, varying current, pulse on time, pulse off time, wire tension, and wire feed. Their study highlighted pulse on time as the most critical process parameter influencing kerf width outcomes.

These studies collectively contribute to understanding how varying parameters in WEDM can be optimized to achieve minimal kerf width, enhancing machining precision and efficiency across different materials and composite structures.

6. Conclusion:

After conducting an extensive literature review, several key findings have emerged. The research prominently focuses on exploring WEDM processes applied to superalloys and composites. Experimental evidence consistently shows that increasing parameters such as pulse on time (T_{ON}), servo voltage (SV), and peak current (I) contribute significantly to improving surface quality. In contrast, pulse on time, wire tension, and wire feed are found to have minimal impact on material removal rate (MMR) or surface roughness (SR).

Furthermore, the majority of research efforts have concentrated on enhancing and optimizing conventional performance measures like MMR, SR, and kerf width (KW) across diverse materials. However, critical performance metrics such as dimensional deviation, hardness, and gap current have either been overlooked or insufficiently addressed in existing studies. This highlights a clear need for further exploration and investigation in these specific areas to deepen our understanding of how WEDM parameters influence these overlooked or underexplored aspects.

In conclusion, the literature review underscores the necessity of broadening the scope of investigation to encompass a more comprehensive range of performance metrics within the realm of WEDM processes. This expansion promises to enhance overall understanding and application of WEDM across various manufacturing contexts.

References

[1]. Kapoor, Jatinder, Sehijpal Singh, and Jaimal Singh Khamba. "High-performance wire electrodes for wire electrical-discharge machining–a review." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226.11 (2012): 1757-1773.

[2]. Sharma, Neeraj, Rajesh Khanna, and Rahuldev Gupta. "Multi quality characteristics of WEDM process parameters with RSM." Procedia Engineering 64 (2013): 710-719.

[3]. Sahoo, Sarat Kumar, Sunita Singh Naik, and Jaydev Rana. "Optimisation of WEDM process parameters during machining of HCHCr steel using TOPSIS method." International Journal of Process Management and Benchmarking 9.2 (2019): 216-231.

[4]. Singh, Harvinder, Vinod Kumar, and Jatinder Kapoor. "Multi-response optimization of WEDM process parameters during the fabrication of microchannels for industrial applications." Materials Today: Proceedings 46 (2021): 81-88.

[5]. Singh, Hari, and R. Garg. "Effects of process parameters on material removal rate in WEDM." Journal of achievements in materials and manufacturing engineering 32.1 (2009): 70-74

[6]. Mahapatra, S. S., and Amar Patnaik. "Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method." The International Journal of Advanced Manufacturing Technology 34 (2007): 911-925.

[7]. Kumar, Rajender, Puneet Katyal, and Shiwani Mandhania. "Grey relational analysis based multiresponse optimization for WEDM of ZE41A magnesium alloy." International Journal of Lightweight Materials and Manufacture 5.4 (2022): 543-554.

[8]. Ehsan Asgar, M., & Singh Singholi, A. K. (2018, September). Parameter study and optimization of WEDM process: A Review. In Iop conference series: Materials science and engineering (Vol. 404, p. 012007). IOP Publishing.

[9]. Boujelbene, M., Ezzdini, S., Elboughdiri, N., Salem, W. B., & Youssef, W. (2017). Investigation on the surface roughness of the high steel material after wire electrical discharge machining process. International Journal of Advanced and Applied Sciences, 4(5), 130-136.

[10]. Shather, Saad Kariem, Abbas Fadhil Ibrahim, and Diana Abed al kareem Noori. "Experimental investigation to predict metal removal and surface roughness in wire cut process." Diyala Journal of Engineering Sciences (2016): 49-58

[11]. Rathod, L., N. S. Poonawala, and R. Rudrapati. "Multi response optimization in WEDM of H13 steel using hybrid optimization approach." IOP Conference Series: Materials Science and Engineering. Vol. 814. No. 1. IOP Publishing, 2020.

[12]. Patel, Vijay D., and Rajeev V. Vaghmare. "A review of recent work in wire electrical discharge machining (WEDM)." International Journal of Engineering Research and Applications 3.3 (2013): 805-816.

[13]. Complete EDM handbook compliments of www.reliable EDM. Com

[14]. Aidil, A. R. M., M. Minhat, and N. I. S. Hussein. "Current research trends in wire electrical discharge machining (WEDM): a review." Journal of Advanced Manufacturing Technology (JAMT) 12.1 (1) (2018): 11-24

[15]. Ali, Muayad M., and Abbas F. Ibrahim. "Effect of machining parameters on surface roughness and metal removal rate for AISI 310 L stainless steel in WEDM." Engineering and Technology Journal 40.01 (2022): 181-188.

[16]. Kumar, Anish, Dr Vinod Kumar, and Dr Jatinder Kumar. "A review on the state of the art in wire electric discharge machining (WEDM) process." International Journal of Mechanical Engineering Research and Development (IJMERD) 1.1 (2011).

[17]. Khan, Z. A., Siddiquee, A. N., Khan, N. Z., Khan, U., & Quadir, G. A. (2014). Multi response optimization of wire electrical discharge machining process parameters using Taguchi based grey relational analysis. Procedia Materials Science, 6, 1683-1695.

[18]. Bobbili, R., Madhu, V., & Gogia, A. K. (2015). Multi response optimization of wire-EDM process parameters of ballistic grade aluminium alloy. Engineering science and technology, an international journal, 18(4), 720-726

[19]. Priyan, M. Shunmuga, et al., "Investigation of surface roughness and MRR on stainless steel machined by wire EDM." International Journal of Engineering Research and Technology 5.3 (2016).

[20]. Thi Hong, T., Do Tam, T., Nguyen, M. C., Anh Tung, L., Ngoc Pi, V., Le Ky, H., & Tien Dung, H. (2019). Effects of process parameters on surface roughness in wire-cut EDM of 9CRSI tool steel. International Journal of Mechanical Engineering and Technology, 10(3).

[21]. El-Bahloul, S. A. (2020). Optimization of wire electrical discharge machining using statistical methods coupled with artificial intelligence techniques and soft computing. SN Applied Sciences, 2, 1-8.

[22]. Hema, P., & Aparna, K. (2021, April). Process parameter optimization of wire EDM on weldment of Monel 400 and AISI 316 grade steel. In IOP Conference Series: Materials Science and Engineering (Vol. 1132, No. 1, p. 012027). IOP Publishing.

[23]. Murali, G., Murugan, M., Arunkumar, K., Elumalai, P. V., Mohanraj, D., & Prabhakar, S. (2022). Investigation and Process Parameter Optimization on Wire Electric Discharge Machining of Aluminium 6082 Alloy. Advances in Materials Science and Engineering, 2022.

[24]. Rao, C. M., & Subbaiah, K. V. Optimization of Wire EDM Process Parameters in Machining SS316 Using DEAR Method (.2021)

[25]. Sapit, Azwan, Shather, Saad, & Nehad, Farook. (2021). Parameters analysis in wire electric discharge machine process of titanium alloys with dielectric alumina. Journal of Materials Today: Proceedings, 10.1016/J. matpr.2020.12.216

[26]. Jha, Mukulanand, Rajiv Kumar Garg, & Shekhar Shrivastava. "Experimental investigation and optimization of WEDM process for AISI 420 stainless steel." IOP Conference Series: Materials Science and Engineering. Vol. 1259. No. 1. IOP Publishing, 2022.
[27]. Uday Kiran Kandala, A. V., Solomon, D. G., & Arulraj, J. J. (2022). Advantages of taguchi method compared to response surface methodology for achieving the best surface finish in wire electrical discharge machining (WEDM). Journal of Mechanical Engineering (JMechE), 19(1), 185-200.
[28]. Naeim, N., AbouEleaz, M. A., & Elkaseer, A. (2023). Experimental Investigation of Surface Roughness and Material Removal Rate in Wire EDM of Stainless Steel 304. Materials, 16(3), 1022
[29]. SAIF, M., & Rawat, R. K. (2023). Investigation of aluminum alloy 6061 in Wire-EDM regarding surface roughness and material removal rate by adopting optimization techniques. Journal of Mechanical Engineering and Sciences, 9410-9420.
[30]. Hammami, D., Louati, S., Masmoudi, N., & Bradai, C. (2023). Influence of WEDM process parameters on aluminum alloy's surface finish. The International Journal of Advanced Manufacturing Technology, 126(1-2), 453-469.
[31]. Devarasiddappa, D., M. Chandrasekaran, and R. Arunachalam. "Experimental investigation and parametric optimization for minimizing surface roughness during WEDM of Ti6Al4V alloy using modified TLBO algorithm." Journal of the Brazilian Society of Mechanical Sciences and Engineering 42 (2020): 1-18.
[32]. Kumar, Anish, Vinod Kumar, and Jatinder Kumar. "Multi-response optimization of process parameters based on response surface methodology for pure titanium using WEDM process." The International Journal of Advanced Manufacturing Technology 68 (2013): 2645-2668.
[33]. Das, P. P., Diyaley, S., Chakraborty, S., & Ghadai, R. K. (2019). Multi-objective optimization of wire electro discharge machining (WEDM) process parameters using grey-fuzzy approach. Periodica Polytechnica Mechanical Engineering, 63(1), 16-25.
[34]. Priyadarshini, M., Biswas, C. K., & Behera, A. (2019, February). Grey-Taguchi optimization of Wire-EDM parameters for P20 tool steel. In Proceedings of the 5th International Conference on Mechatronics and Robotics Engineering (pp. 5-8).
[35]. Pramanik, A., Basak, A. K., Dixit, A. R., & Chattopadhyaya, S. (2018). Processing of duplex stainless steel by WEDM. Materials and Manufacturing Processes, 33(14), 1559-1567
[36]. Chaudhary, Tina, et al., "multi-response optimization for Nimonic alloy miniature gear fabrication using wire electrical discharge machining." Advances in Mechanical Engineering 12.10 (2020): 1687814020967580
[37]. Kalyanakumar, S., Prabhu, L., Saravanan, M., & Imthiyas, A. (2020, December). Experimental investigation of MRR, RA of 304 stainless steel using WEDM. In IOP Conference Series: Materials Science and Engineering (Vol. 993, No. 1, p. 012035). IOP Publishing.
[38]. Basavaraju, H. R., S. S. Manjunatha, and R. Suresh. "Investigation on Surface Roughness and MRR in WEDM of Titanium Grade 7 (Ti-0.15 Pd) Alloy using Statistical Techniques." Journal of Mechanical Engineering (1823-5514) 20.2 (2023).
[39]. Kumar, Pawan, Meenu Gupta, and Vineet Kumar. "Microstructural analysis and multi response optimization of WEDM of Inconel 825 using RSM based desirability approach." Journal of the Mechanical Behavior of Materials 28.1 (2019): 39-61.
[40]. Kumar, S. Suresh, Erdemir, F., Varol, Temel, Kumaran, S. Thirumalai, Uthayakumar, M., Canakci, Aykut (2020) Investigation of WEDM process parameters of Al–SiC–B4C composites using response surface methodology. International Journal of Lightweight Materials and Manufacture-3-2-127-135-2020.
[41]. Sridhar, Kandukuri, and G. Gopinath. "OPTIMIZATION OF PROCESS PARAMETERS FOR WIRE CUT EDM OF H-13 HOT DIE TOOL STEEL BY GREY RELATIONAL ANALYSIS."
[42]. Shinde, Babasaheb, and Raju Pawade. "Study on analysis of kerf width variation in WEDM of insulating zirconia." Materials and Manufacturing Processes 36.9 (2021): 1010-1018.
[43]. Ishfaq, K., Ahmad, N., Jawad, M., Ali, M. A., & M. Al-Ahmari, A. (2019). Evaluating material's interaction in wire electrical discharge machining of stainless steel (304) for simultaneous optimization of conflicting responses. Materials, 12(12), 1940.
[44]. Bagal, D. K., Barua, A., Jeet, S., Satapathy, P., & Patnaik, D. (2019). MCDM optimization of parameters for wire-EDM machined stainless steel using hybrid RSM-TOPSIS, genetic algorithm and simulated annealing. Int J Eng Adv Technol, 9(1), 366-371.
[45]. Muniappan, A., C. Thiagarajan, and S. Somasundaram. "Optimization of kerf width obtained in WEDM of aluminum hybrid composite using Taguchi method." ARPN J. Eng. Appl. Sci 12 (2017): 382-388.
[46]. Ablyaz, T. R., Shlykov, E. S., Muratov, K. R., & Sidhu, S. S. (2021). Analysis of wire-cut electro discharge machining of polymer composite materials. Micromachines, 12(5), 571.
[47]. Pujara, J. M., K. D. Kothari, and A. V. Gohil. "An investigation of material removal rate and kerf on WEDM through grey relational analysis." Journal of Mechanical Engineering and Sciences 12.2 (2018): 3633-3644.
[48]. Nawaz, Y., Maqsood, S., Naeem, K., Nawaz, R., Omair, M., & Habib, T. (2020). Parametric optimization of material removal rate, surface roughness, and kerf width in high-speed wire electric discharge machining (HS-WEDM) of DC53 die steel. The International Journal of Advanced Manufacturing Technology, 107, 3231-3245.
[49]. Goyal, Ashish, and H. U. Z. E. F. Ur Rahman. "Experimental studies on Wire EDM for surface roughness and kerf width for shape memory alloy." Sādhanā 46.3 (2021): 160

[50]. Verma, Ramesh Kumar, Rajeev Kumar Upadhyay, and Syed Asghar Husain Rizvi. "Modeling of kerf width during WEDM of die steel D3." Materials Today: Proceedings 54 (2022): 832-838.