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A review on Wire-EDM of bio titanium

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ABSTRACT

Nonconventional machining technologies have been found viable to manufacture various products from a wide range of engineering materials. Wire electric discharge machining (WEDM), also known as Wire-EDM, is one of the important thermal type nonconventional machining technologies. Wire-EDM is being preferably used by manufacturers to produce biomedical devices including bio and dental implants. This paper presents an overview of capabilities of wire-EDM type nonconventional machining technology for the precise machining of titanium and its alloys for biomedical applications. It reviews the important research work conducted on machining titanium alloys by wire electrical discharge machining (WEDM). Their findings and achievements are discussed to encourage further research and development in the biomaterial machining area.

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1. Introduction

The demands for novel biomaterials and their processing and fabrication techniques are increasing very rapidly due to the accelerated demands of bioimplants [Prakash et al, 2015; Davis et al., 2022; Amin et al., 2021; Li et al, 2014]. Biomaterials are distinct from conventional materials due to applications and are widely used for manufacturing biomedical and dental implants such as artificial teeth, orthopedic, heart-valves, artificial-hearts, vascular-grafts, bone plates, wires, fixtures, pins, rods, and screws. A bioimplant is an artificial organ used to treat a diseased natural organ or tissue without harming other body parts. Biomaterials used for biomedical and dental applications are metallic and non-metallic. Compared to other biomaterials, metal biomaterials are the best options for the replacement of hard body tissues such as hip and knee joints due to excellent mechanical strength, superior biological compatibility, and anti-corrosion properties. Globally, a large volume of bio-implants is manufactured from metallic bio-materials due to their high mechanical strength, stiffness, and durability [Aliyu et al., 2017; Amin et al., 2020; Niinomi et al., 2012]. A wide range of biomaterials such as stainless steel, titanium and its alloys, nitinol, Mg based alloys, and Co-Cr alloys, are commonly used. Titanium material is mostly used in implants and screws, hip replacement, spherical prosthesis, pacemakers casing, spine, and trauma systems.

To manufacture bio-implants and other biomedical devices, biomaterials like titanium and its alloys have to undergo extensive machining [Stojković et al., 2023]. Their machining by conventional or traditional processes like drilling, milling, and turning etc. is challenging due to high hardness, low elastic modulus, low thermal conductivity of titanium and its alloys. It often results out in frequent and severe tool wear, deterioration in surface quality, machining inaccuracy, and defects like crack, burr, and nicks etc. [Hashmi et al., 2023; Sidhu 2021]. This attracted researchers to explore nonconventional or modern machining processes to machine titanium type difficult-to-machine materials for manufacturing of bioimplants with good part quality and process productivity. Wire electrical discharge machining (WEDM) is a variant of electric discharge machining (EDM) which is a nonconventional process [Sidhu, 2021; Haque et al., 2023]. It‘s capabilities have been explored by many researchers to machine difficult-to-machine materials like titanium. The major applications of WEDM in biomedical industry are (i) for machining high-aspect-ratio standard and non-standard long and precise holes or tunnels for drug delivery; (ii) to fabricate die and mold for medical implants; (iii) for making fixtures and screws for biomedical implants; (iv) for making a variety of tiny features for biomedical implants; (v) for manufacturing medical instruments. Femoral and cut guides, tibial cut guides, resection cut blocks, endoscopy components, laparoscopic graspers and forceps, bone plates, surgical needles, and alignment guides are some typical biomedical parts and components fabricated by WEDM [Sidhu, 2021].

1.1. Working principle of wire electrical discharge machining (WEDM)

WEDM is a spark erosion based thermal type nonconventional machining process [Pop et al., 2019; Akincioglu, 2022; Singh et al., 2023]. This process can be used to machine all kinds of electrically conducting materials, irrespective of their hardness and thickness using a fine thin electrically conductive wire made of brass, molybdenum, and zinc-coated brass materials. Brass and zinc-coated wire are frequently used for machining. In this process, materials are removed from work material in the form of fine particles known as debris due to thermoelectric erosion. Thermoelectric erosion of work material takes place due to occurrence of a series of recurring electrical sparks between the outer surface of the wire and the work material. A direct current (DC) supply is used for the generation of electrical sparks. The surface area of the wire and work material that comes in contact with sparks is heated to extremely high temperatures (approximately 12000 0C), causing melting and vaporizing of both materials and then continues flowing deionized water also serves as dielectric flushes away the removed particles from machining zone (i.e. inter-electrode gaps) to ensure smooth machining by avoiding wire breakage and formation of recast layer on the machined surface. Microcracks, voids, nicks, and asperities are components of the recast layer that significantly degrade the quality of machined surfaces. An interelectrode gap IEG (about 0.025 mm) is maintained by a servo mechanism to avoid short-circuiting or excess gaps causing uneven machining. Wire and work materials are connected to the negative and positive poles of the DC supply. The power supply system, dielectric supply system, servo mechanism, and wire drive system are the main components of WEDM. Worktable can move along X and Y axis as per the part program. U and V are auxiliary axes to tilt wire along X and Y direction by the ram to perform taper machining. Fine wire travel through the upper and lower guide. these guides are used to maintain the wire tension between stand-off distances. Both guides are attached with nozzles for localized flushing of dielectric on the machining zone where the occurrence of sparks takes place to avoid wire breakage due to excessive heat. Localized flushing is maintained by a pump and filter during machining. The lower guide is fixed while the upper guide is attached with a ram and moves up and down along the Z axis by a stepper motor. Wire fed from the supply spool then vertically travels through upper and lower guides through work material and is collected by take-off spool as shown in Figure 1.

The concept of material erosion in WEDM is shown in Figure 2. Material erosion takes place in three stages namely preparation phase (a-b), discharge phase (b-c), and interval phase (c-d) [Jain and Gupta, 2020; Biswas, 2023]. When DC power is applied, a strong electrical field develops at the least IEG. Due to this, suspended microscopic contaminants in the dielectric accumulated at the strongest point of the electric field and thus forming the highly conductive bridge across the IEG. Wire, work material, and formed bridge continuously heated due to continuous increment of applying voltage and thus build a spark channel due to ionization of a small portion of the conductive bridge (preparation phase). When applying voltage exceeds dielectric breakdown results in a sudden increase of temperature and pressure causing the collapse of the bridge. Due to this collapse, sparks generate between IEG and a tiny amount of material is melted and vaporized from both the wire and work material surface where sparks take place. A gaseous bubble made of vaporization byproducts quickly spreads beyond spark channels (phase of discharge). During the spark-off duration, material erosion stopped due to the collapse of plasma channels, and dielectric flushes away the eroded particles from the machining zone (interval phase). This procedure is carried out or repeated until the workpiece has been completely machined.

Important process parameters and performance measures of WEDM are shown in Figure 3.

In this review article, a systematic review of the previous research carried out on the machining of titanium and its alloys by WEDM is reported (i) to highlight the WEDM's capability to machine better quality biomedical parts, and (ii) to highlight the previous work’s outcomes and achievements.

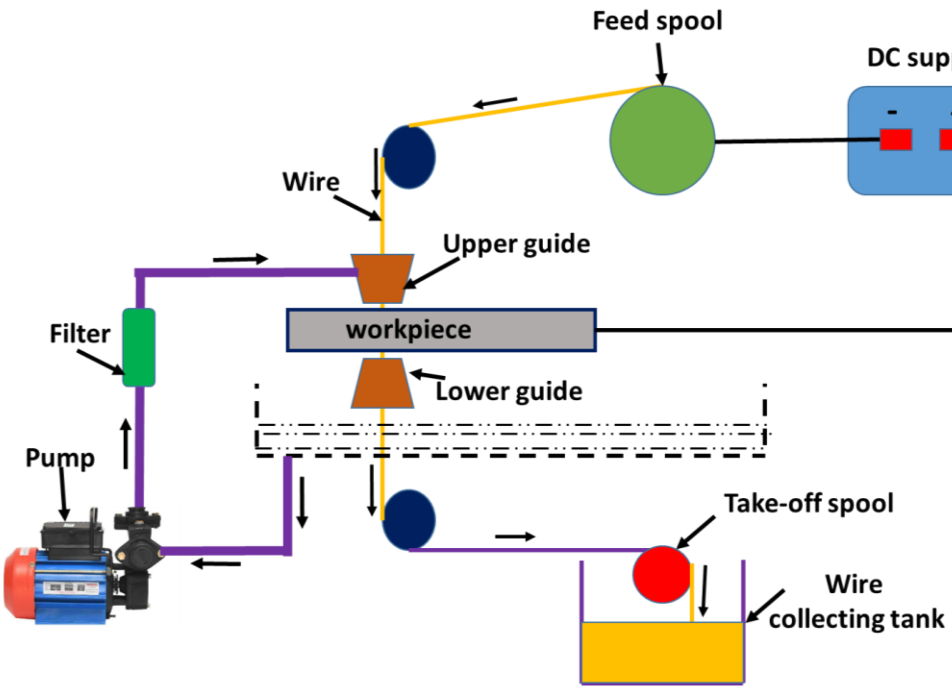


Figure 1. This is a Schematic representation of the working principle of the WEDM process

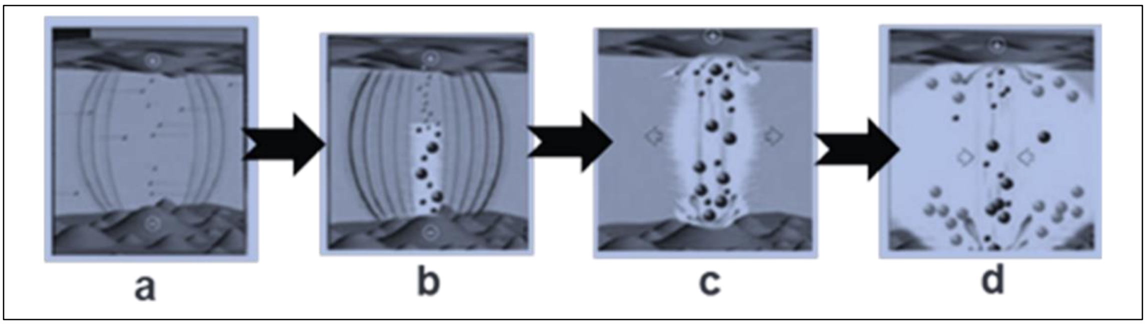


Figure 2. Concept of material erosion in WEDM process

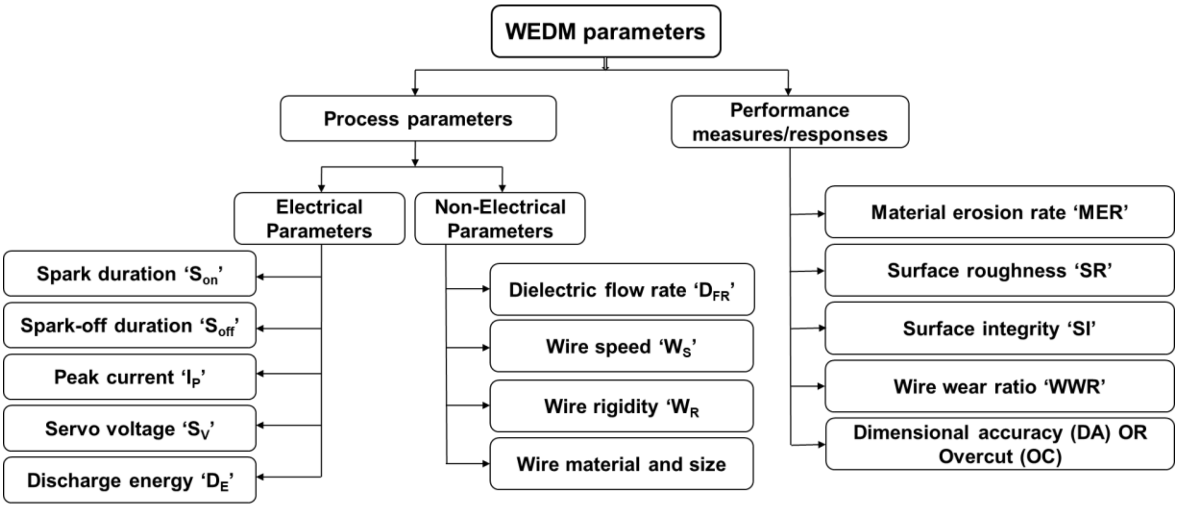


Figure 3. Generalized process parameters and performance measures of WEDM process

2. Review of Past Work on WEDM of Titanium and Alloys

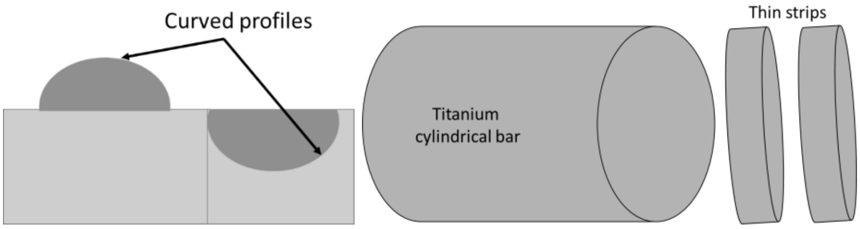
The available literature shows that substantial research attempts have been made on the machining of biomaterials including titanium, by WEDM in the past decade. Table 1 presents a systematic summary of the important past work conducted on the machining of titanium and its alloy by WEDM. Some important past attempts are discussed here as under:

Farooq et al. (2020) successfully attempted machining of curved profiles on biotitanium (grade 5) plate using WEDM. They identified 70 V servo voltage; 40 µs pulse-off duration, and 6 mm/s wire-speed as optimal parameters for minimum profile deviation. Voltage and pulse-off time were identified as the most significant parameters. Pramanik et al. (2019) studied the effects of pulse on time, flushing pressure, and wire tension on surface roughness, kerf width, discharge gap, material removal rate, and wire degradation for machining of 9 mm thick titanium (Ti6Al4V alloy) plate at ten different machining combination by WEDM using zinc-coated wire. They observed the presence of a recast layer and an increase in kerf width when machining is done at long pulse on time due to high discharge energy. Sharma et al. (2022) improved the surface quality of titanium grade 2 part by optimizing WEDM parameters using a hybrid technique of evaluation based on distance from average solution ‘EDAS‘ and particle swarm optimization ‘PSO‘. The optimum combination of parameters was 8 µs as pulse duration; 13 µs as pulse-off duration; 45 V as servo voltage; and 8 N as wire rigidity for 95% dimensional accuracy; 3.163 µm average roughness; and 22.99 µm mean roughness depth. According to an important study, WEDM can significantly improve wear and fatigue resistance by developing a non-corrosive and biocompatible protective layer on the machined surface of Ti-6Al-4V ELI alloy after trim machining and thus enhances its service life and functional performance for biomedical applications [Manderna et al., 2022]. Wear and corrosion behavior of titanium were examined after two stages of machining by WEDM namely rough and trim cut. The trim cut was carried out to remove the deposited recast layer on the titanium top machined surface after rough machining by WEDM varying pulse duration; pulse-off duration; peak current; servo voltage; wire speed and wire rigidity. WEDM machined surface after trim-cut was found to have lesser wear rate than rough. Whereas, corrosion rates vary between 0.2152 mm/year to 0.6921 mm/year for each machined surface obtained by rough and trim machining by WEDM.

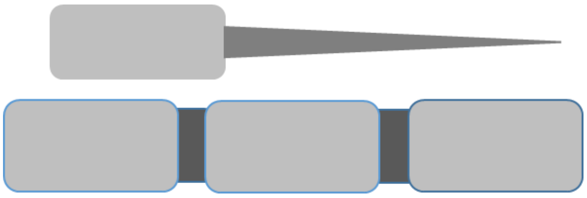
In another study, the effect of wire in WEDM was studied [Manupati et al., 2019]. Higher material erosion rate and better surface quality were achieved while machining pure titanium using annealed wire in WEDM. Pulse duration was found as the most significant parameter in WEDM of titanium and its alloys [Arikatla et al., 2017]. A successful optimization of WEDM for surface quality improvement of Ti Alloy 6242, was conducted by Das et al. (2021). A recent investigation highlights the importance of wire coating for performance improvement of WEDM for machining bio titanium [Samson et al., 2022]. Zinc cozted brass wire was found effective in material rate improvement and recast layer reduction. Prakash et al. (2022) found favourable corrosion behavior, mechanical and tribological characteristics of Ti6al4v, machined by WEDM. Kumar et al. (2019) found good metallurgical properties for WEDM machined titanium. Devarasiddappa and Chandrasekaran (2020) obtained optimized surface quality and productivity when conducted optimization of WEDM of Ti6Al4V using teaching learning-based optimization technique. Their scanning electron microscopy study revealed smooth machined surface of biotitanium that was free from micro-cracks, voids, and other surface defects. An interesting study revealed the superiority of molybdenum wire over brass wire for machining titanium alloy by WEDM [Oliver et al., 2017]. The outcomes indicate obtaining better machinability indicators i.e. surface roughness and material erosion rate and smoother surface morphology. In literature, effectiveness of evolutionary techniques like artificial neural network and genetic algoritham etc. is reported for modeling and optimization in machining thin pieces of biotitanium by WEDM [Bose and Nandi, 2023; Paturi et al., 2022].

Mahbub et al. (2022) studied the surface roughness, microstructure, phase transformation, and recast layer of the WEDM machined titanium grade 5 (Ti-6Al-4V) alloy. During biocompatability testing, it was found positive relationship between cell attachment and surface finish. WEDM machined titanium surface revealed higher cell attachment than the traditionally machined surface. Research findings revealed that WEDM can manufacture bio-parts and components with improved biocompatibility. While machining biotitanium at parameters settings prone to rapid heating and cooling in WEDM, surface quality deterioration in the form of presence of recast layer, occurrence of cracks and burrs, and formation of globules etc., was also observed [Kumar et al., 2021]. Hardened titanium alloy was also found quite effective in terms of surface quality, when machined using WEDM [Gupta et al., 2019]. Mechanical properties were also found important to obtain the desired surface roughness values on titanium and its alloys during machining by wedm for biomedical applications [Mouralova et al., 2016]. WEDM of titanium at an angle to impart a definate shape to the resulting product, was also made possible in a past study [Wasif et al., 2020].

In literature, a variety of research attempts on Wire-EDM of nickel titanium shape memory alloy, also known as nitinol, for a wide range of bio applications, have been found [Wang et al., 2018; Chaudhari et al., 2020; Hou et al., 2022; Kulkarni et al., 2020]. NiTi materials also possess excellent biocompatibility and found applications in cardiovascular stents, micro-actuators, and dental implants etc. Modeling and optimization-based studies were majorly conducted for improvement in WEDM productivity and NiTi quality [Gupta, 2021; Majumder and Maity, 2018]. Some machining examples showing the capability of WEDM are shown in Figures 4 and 5.

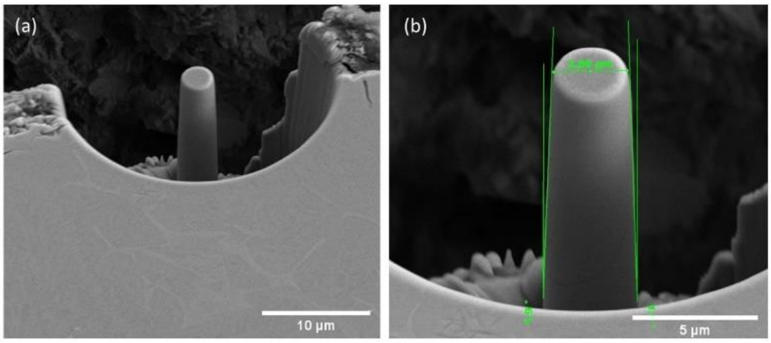


(a) Curved profiles (b) Thin strips

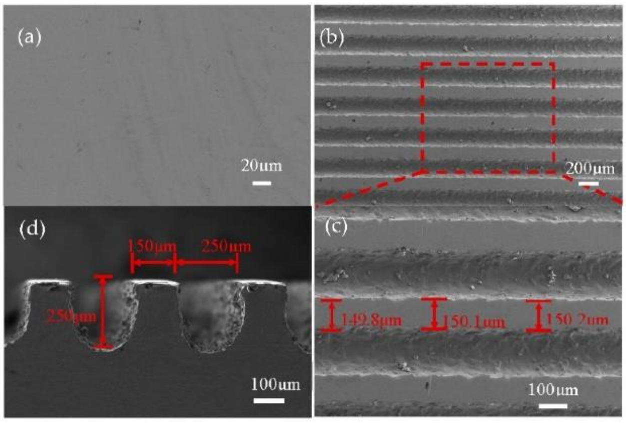


© Micro-pins and -slots

Figure 4. Machined shapes and features by WEDM on Titanium and its alloys



(a) Micropillars [41]



(b) Microgrooves [42]

Figure 5. Some of the part examples machined by WEDM from titanium

Table 1. Summary of recent research work done on the machining of biocompatible titanium and its alloys by WEDM

Researchers (Year)	Methodology and optimization techniques	Machining details (i.e. biomedical workpiece and tool electrode materials)	Selected variable parameters	Selected responses	Key findings
Farooq et al. (2020)	Curved cutting L27 orthogonal array with thrice replication Wire offset: 0.125 mm	Ti6Al4V (grade 5) (300 _ 100 _ 10mm) Brass wire (ϕ: 0.25 mm) Deionized water	Pulse duration (T_{on}), pulse-off duration (T_{off}), servo voltage (V_S), and wire speed (W_S)	Prelim: Wire breakage Main: Profile deviation	• Successfully generate a curved profile on a titanium grade 5 rectangular plate with 0.23 and 0.236% profile deviation.
Pramanik et al. (2019)	Straight cutting Taguchi, ANOVA, $L_{54}(3^6)$	Ti6Al4V alloy (9 mm thick plate) Zinc-coated brass wire (ϕ: 0.25 mm) Dielectric: TEM oil	Pulse duration; flushing pressure; and wire tension	Ra, KW, discharge gap, MER and wire degradation	• Roughness decreases with a shorter pulse duration whereas no variation in performance measures has been observed for flushing pressure and wire rigidity. • Formation of recast layer on the top machined surface of the titanium. • Kerf width increase with pulse duration at both the top and bottom of the grooves.
Sharma et al. (2022)	Factorial design (two-level), EDAS-PSO	Pure titanium alloy (grade 2), cylindrical plate (ϕ: 25 mm, L: 300 mm), Zinc-coated brass wire (ϕ = 0.25 mm)	Pulse duration, pulse-off duration, servo voltage and wire rigidity	Ra; R_Z and DA	• Successfully implemented EDAS-PSO optimization technique • SEM images of optimized species revealed better surface quality.
Manderna et al. (2021)	Straight cutting Taguchi L_9 (3^4) S/N ratio	Titanium alloy (Ti-6Al-4V ELI) Brass wire (ϕ: 0.25 mm)	Pulse duration; pulse-off duration; peak current; servo voltage; wire speed and wire rigidity	Wear and corrosion	• Improve wear and fatigue resistance of titanium machined surface after WEDM trim cut. • Trim-cut has a lesser wear rate of 65.73 x 10-2 mm^3/min than rough cut 67.51 x 10-2 mm^3/min. • Corrosion rates vary between 0.2152 mm/year to 0.6921 mm/year.
Manupati et al. (2019)	Straight cutting Taguchi L_9 (3^4) S/N ratio	Pure Titanium (Grade-2) Zinc-coated and annealed wire (ϕ: 0.25 mm)	Pulse duration; pulse current; servo voltage; wire speed and wire rigidity	SR and MER	• Higher MER and better surface can be achieved by annealed wire than zinc-coated wire. • SEM analysis revealed lower contamination on the titanium surface machined by annealed wire.

Arikatla et al. (2017)	Straight cutting RSM; ANOVA	Titanium (Ti-6Al-4V) Alloy' Brass wire (ϕ: 0.25 mm)	Pulse duration, pulse-off duration, servo voltage, input power, and wire rigidity	MER; SR and kerf width	Developed models to predict MER, SR, and KW. Pulse duration and input power have a significant influence on MER, SR, and kerf width.
Daniel et al. (2021)	TOPSIS Taguchi L_{27} (3^4) S/N ratio	Titanium alloy (Ti Alloy 6242) Rectangular plate (10 mm×10 mm×5 mm) Brass wire (ϕ: 0.25 mm)	Voltage, pulse duration, pulse-off duration, and wire speed	R_a and MER	TOPSIS technique was used to identify optimal parameters to maximize MER and minimize R_a. Identified optimal values 2.5211 mm^3/min and 2.4796 µm as MER and Ra, respectively.
Samson et al. (2022)	TOPSIS Taguchi L_9 (3^3)	Medical grade titanium alloy (Ti-6Al-4V) rectangular plate (10 mm×20 mm ×20 mm) Zinc-coated brass wire and heat-treated brass wire (ϕ: 0.25 mm)	Pulse duration, pulse-off duration, and wire speed	R_a, MER, TWR, RLT	Evaluate the performance of zinc-coated wire and heat-treated brass wire for machining titanium alloy by WEDM. Zinc-coated wire performed superior to the heat-treated brass wire. Higher MER along with lower RLT and TWR can be achieved by zinc-coated wire.
Prakash et al. (2022)	BBD, RSM DFA	Medical grade titanium alloy (Ti-6Al-4V) rectangular plate) Brass wire (ϕ: 0.25 mm)	Pulse duration, pulse-off duration, and wire rigidity	R_a and MER	HAp-coated titanium has better corrosion resistance and mechanical and tribological characteristics than pure titanium. DFA was used to maximize MER and minimize Ra.
Kumar et al. (2019)	BBD, RSM ANOVA	Medical grade titanium alloy (Ti-6Al-4V) rectangular plate half-hard brass wire (ϕ: 0.25 mm)	Voltage, pulse duration, and pulse-off duration	MER and R_a	SEM examination with EDS of the optimized surface revealed incomplete infusion as metal oxides. Voltage has a significant influence on considered responses. Observed minimum Ra at higher voltage whereas maximum Ra at low voltage.
Devarasiddappa and Chandrasekaran (2020)	Taguchi L_{16} (4^4)	Titanium alloy (Ti-6Al-4V) Molybdenum wire (ϕ = 0.18 mm)	Pulse duration, pulse-off duration, peak current, and wire speed	MER and SR	Successfully performed machining on titanium by WEDM.
Raj and Prabhu (2016)	Taguchi L_9 (3^3)	Titanium alloy Rectangular plate Brass and Molybdenum wires (ϕ = 0.25 mm)	Pulsed current, pulse duration, and pulse-off duration	MER and SR	Found that molybdenum wire is superior to brass wire for machining titanium alloy. Peak current and pulse duration have a significant influence on SR and MER
Bose and Nandi (2022)	--	Titanium matrix composite (TMC)	Power, pulse-off duration, and peak current	MER, SR. OC and KW	Multi-objective genetic algorithm (MOGA) with desirability were used for multi-objective optimization. Results of optimization were validated experimentally by conducting a confirmation experiment.

		Brass wire (ϕ = 0.25 mm)			
Paturi et al. (2022)	Taguchi L_{27} (3^8), ANOVA, ANN	Titanium (Ti-6Al-4V) Rectangular plate (200mm x 110mm x 11mm) Brass wire (ϕ = 0.25 mm)	Pulse duration, pulse-off duration, wire speed, arc-on duration, arc-off duration, servo voltage, flushing pressure, and wire rigidity	SR, MER, CS, and KW	Predicted values of responses by ANN models have revealed a close agreement with experimental data. For all datasets, the proposed ANN method produced a good fit for the model data, with an R-value of above 0.99.
Mahbub et al. (2022)	---	Titanium grade 5 (Ti-6Al-4V) Brass wire (ϕ = 0.25 mm)	--	----	Concluded that WEDM can manufacture bio-implants with improved biocompatibility.
Kumar et al. (2021)	ANOVA, DFA	Titanium grade 5 (Ti-6Al-4V) Brass wire (ϕ = 0.25 mm)	Pulse duration pulse-off duration, pulsed current, and servo voltage	SR, MER, crack density (CD), and white layer thickness (WLT)	Found pulse duration pulse-off duration, pulsed current, and servo voltage as the most significant factors. Formation of deeper and wider craters, globules of debris, micro-cracks, and WLT at higher values of significant WEDM parameters.
Gupta et al. (2021)	BBD, RSM	Pure titanium alloy (Ti-6Al-4V), rectangular plate (-) Copper wire (ϕ = 0.25 mm)	Servo reference voltage, wire speed, and wire rigidity	Cutting speed (CS)	SEM images revealed that hardened titanium alloy had better surface qualities as compared to titanium alloys.
Mouralova et al. (2016)		Pure titanium alloy (Ti-6Al-4V) Brass wire (ϕ = 0.25 mm)	Pulse duration, pulse-off duration, servo voltage, wire speed, and discharge current.	S-parameters of SR	The observed lowest value of S-parameters in titanium alloy compared to aluminum alloy. Mechanical properties of the material also decide the S-parameters of the machined surface.

MER- material erosion rate, SR- surface roughness, WWR- wire wear rate, KW- kerf width, CS- cutting speed, WLT- white layer thickness, CD- crack density, RSM- response surface methodology, BBD- Box behnken design, RLT- recast layer thickness, TWR- tool wear rate, DA- dimensional accuracy, ANOVA- analysis of variance, OC- overcut, DC-direct current, Ra- average surface roughness, Rz- mean roughness depth, Ton- Pulse duration/time, Toff- pulse off duration/time, VS- servo voltage, WS- wire speed

3. Conclusions and Future Research Directions

The following conclusions can be drawn from the review of past work on WEDM of titanium and its alloys for biomedical applications:

- A variety of parts and products can be made from titanium and its alloys using WEDM.
- It requires low discharge energy parameter settings in WEDM to obtain the high surface quality of titanium bioproducts.
- Modeling and optimization techniques can be of great assistance to enhance the machinability of WEDM of bio titanium for quality and productivity improvement.
- A limited work has been conducted on taper machining, curved profile cutting, and turning by WEDM and its variants.
- A very little work has been reported to identify the effect of wire materials and other machining parameters on performance of WEDM for machining metallic biomaterials.
- The past attempts on sustainability of WEDM are scarce.
- The bio studies of the titanium parts machined by WEDM, are very limited.

The following future research directions are identified:

- Detailed investigation on the sustainability of the WEDM for machining biomaterials.
- Actual bio activity study of the titanium parts machined by WEDM, is required to be investigated
- Fabricating fixtures, screws, trepanning of holes, and bio-parts from a wide range of biomaterials by WEDM.
- Hybridization of the WEDM with other processes for efficient and high-quality manufacturing of bioimplants.
- Using machine learning techniques to optimize the WEDM process for quality enhancement of biomedical products.

References

Akıncıoğlu S. (2022). Taguchi Optimization of Multiple Performance Characteristics in the Electrical Discharge Machining of the Tigr2. Facta Universitatis, Series: Mechanical Engineering, 20(2), 237-253.

Aliyu, A.A.A., Abdul-Rani, A.M., Ginta, T.L., Prakash, C., Axinte, E., Razak, M.A., & Ali, S. (2017). A Review of Additive Mixed-Electric Discharge Machining: Current Status and Future Perspectives for Surface Modification of Biomedical Implants. Advances in Materials Science and Engineering, 8723239, 8723239.

Amin, M.A., Abdul-Rani, A.M., Danish, M., Thompson, H.M., Aliyu, A.A.A., Hastuty, S., Zohura, F.T., Bryant, M.G., Rubaiee, S., & Rao, T.V.V.L.N. (2020). Assessment of PM-EDM cycle factors influence on machining responses and surface properties of biomaterials: A comprehensive review. Precision Engineering, 66, 531-549.

Amin, M., Abdul-Rani, A.M., Danish, M., Rubaiee, S., Mahfouz, A.b., Thompson, H.M., Ali, S., Unune, D.R., & Sulaiman, M.H. (2021). Investigation of Coatings, Corrosion and Wear Characteristics of Machined Biomaterials through Hydroxyapatite Mixed-EDM Process: A Review. Materials, 14, 3597.

Arikatla, S.P, Mannanb, K.T., & Krishnaiah, A. (2017). Parametric optimization in wire electrical discharge machining of titanium alloy using response surface methodology. Materials Today: Proceedings, 4, 1434–1441.

Basak, A., Pramanik, A., Prakash, C., Shankar, S., & Debnath, S. (2022). Understanding the Micro-Mechanical Behaviour of Recast Layer Formed during WEDM of Titanium Alloy. Metals, (12), 188.

Biswas, S., Paul, A.R., Dhar, A.R., Singh, Y., & Mukherjee, M. (2023). Multi-material modeling for wire electro-discharge machining of Ni-based superalloys using hybrid neural network and stochastic optimization techniques. CIRP Journal of Manufacturing Science and Technology, 41, 350-364.

Bose, S., & Nandi, T. (2023). DMOGA on performance measures of WEDM for titanium matrix composite. Materials Today: Proceedings, 78(3), 469-475.

Chaudhari, R., Vora, J.J., Patel, V., López de Lacalle, L.N., & Parikh, D.M. (2020). Surface Analysis of Wire-Electrical-Discharge-Machining-Processed Shape-Memory Alloys. Materials, 13, 530.

Das D.A., Kumar S.K., & Prasanna, R. (2021). Investigating the effect of wire cut EDM of titanium alloy 6242 using TOPSIS. Advances in Materials and Processing Technologies, 8(3), 2824-2836.

Davis, R., Singh, A., Jackson, M.J., Coelho, R.T., Prakash, D., Charalambous, C.P., Ahmed, W., Silva, L.R.R., & Lawrence, & A.A. (2022). A comprehensive review on metallic implant biomaterials and their subtractive manufacturing. International Journal of Advanced Manufacturing Technology, 120, 1473–1530.

Devarasiddappa, D., & Chandrasekaran, M. (2020). Experimental investigation and optimization of sustainable performance measures during wirecut EDM of Ti-6Al-4V alloy employing preference based TLBO algorithm. Materials and Manufacturing Processes 35(11), 1204-1213.

Farooq, M.U., Ali, M.A., He, Y., Khan, A.M., Pruncu, C.I., Kashif, M., Ahmed, N., & Asif, N. (2020). Curved profiles machining of Ti6Al4V alloy through WEDM: investigations on geometrical errors. Journal of materials research and technology, 9(6), 16186-16201.

Gupta, K. (2021). Intelligent Machining of Shape Memory Alloys. Advances in Science and Technology Research Journal, 15(3), 43–53.

Gupta, N.K., Somani, N., Prakash, C., Singh, R., Walia, A.S., Singh, S., & Pruncu, C.I. (2021). Revealing the WEDM Process Parameters for the Machining of Pure and Heat-Treated Titanium (Ti-6Al-4V) Alloy. Materials, 14, 2292.

Hashmi, A.W., Mali, H.S., Meena, A., Saxena, K.K., Ahmad, S., Agrawal, M.K., Sagbas, B., Puerta, A.P.V., & Khan, M.I. (2023). A comprehensive review on surface post-treatments for freeform surfaces of bio-implants. Journal of Materials Research and Technology, 23, 4866-4908.

Haque, R., Sekh, M., Kibria, G., & Haidar, S. (2023). Improvement of Surface Quality of Ti-6al-4v Alloy by Powder Mixed Electrical Discharge Machining Using Copper Powder. Facta Universitatis, Series: Mechanical Engineering, 21(1), 63-79.

Hou, Y., Xu, J., Lian, Z., Zhai, C., Li, M., Yang, S., & Yu, H. (2022). Research on surface microstructures and properties of NiTi shape memory alloy after wire electrical discharge machining. Materials Today Communications, 31, 103521.

Jain, N.K., & Gupta, K. (2020). Spark Erosion Machining- MEMS to Aerospace, CRC Press.

Kulkarni, V.N., Gaitonde, V.N., Karnik, S.R., Manjaiah, M., & Davim, J.P. (2020). Machinability Analysis and Optimization in Wire EDM of Medical Grade NiTi Memory Alloy. Materials, 13, 2184.

Kumar, S., Khan, A.M., & Muralidharan, B. (2019). Processing of titanium-based human implant material using wire EDM. Materials and Manufacturing Processes 34(6), 695-700.

Kumar, A., Sharma, R., & Gujral, R. (2021). Investigation of crack density, white layer thickness, and material characterization of biocompatible material commercially pure titanium (grade-2) through a wire electric discharge machining process using a response surface methodology. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 235(36), 2073-2097.

Li, Y., Yang, C., Zhao, H., Qu, S., Li, X., & Li, Y. (2014). New Developments of Ti-Based Alloys for Biomedical Applications. Materials, 7, 1709-1800.

Mahbub, M.R., Kovach, L., A., Wolfe, M., Lalvani, S., James, P. F., & Jahan, M.P. (2022). Enhancing cell adhesion and corrosion performance of titanium alloy by surface and sub-surface engineering using WEDM. Surface and Coatings Technology, 429, 127929.

Majumder, H., & Maity, K. (2018). Application of GRNN and multivariate hybrid approach to predict andoptimize WEDM responses for Ni-Ti shape memory alloy. Applied Soft Computing, 70, 665-679.

Manderna, S.K., Katyal, P., Gupta, M., & Singh, G. (2022). Wear and corrosion behaviour of wire electrical discharge machined Ti-6A1-4v alloy. IOP Conference Series: Materials Science and Engineering, 1225, 012067.

Manupati, V.K., Rajyalakshmi, G., Varela, M.L.R., Machado, J., & Putnik, G.D. (2019). Investigation of Copper and Zinc Contamination on the Work Piece Surface with WEDM. Innovation, Engineering and Entrepreneurship, 608–615.

Mouralova, K., Kovar, J., & Sliwkova, P. (2016). Evaluation of s-parameters on the surface of titanium alloy TI-6AL-4V and AL99.5 machined by WEDM. MM Science Journal, 2016(December), 1537-1540.

Niinomi, M., Nakai, M., & Hieda, J. (2012). Development of new metallic alloys for biomedical applications. Acta Biomaterialia, 8(11), 3888-3903.

Oliver, S., Raj, N., & Prabhu, S. (2017). Modeling and analysis of titanium alloy in wirecut EDM using Grey relation coupled with principle component analysis. Australian Journal of Mechanical Engineering 15(3), 198-209.

Paturi, U.M.R., Cheruku, S., Salike, S., Pasunuri. V.P.K., & Reddy, N.S. (2022). Estimation of machinability performance in wire-EDM on titanium alloy using neural networks. Materials and Manufacturing Processes, 37(9), 1073-1084.

Prakash, S., Favas, C.S.A., Basha, I.A., Venkatesh, R., Prabhahar, M., Durairaj, V.P., Gomathi, K., & Lenin H. (2022). Investigation of mechanical and tribological characteristics of medical grade Ti6al4v titanium alloy in addition with corrosion study for wire EDM process. Advances in Materials Science and Engineering, 5133610.

Pramanik, A., Basak, A.K., & Prakash, C. (2019). Understanding the wire electrical discharge machining of Ti6Al4V alloy. Heliyon, 5(4), e01473.

Pop, G., Dragomir, M., Titu, A., & Cupsan, V. (2019). Review of wire electrical discharge machining of the aluminum extrusion die. Nonconventional Technologies Review, 23(3), 48-54.

Prakash, C., Kansal, H.K., Pabla, B., Puri, S., & Aggarwal, A. (2015). Electric discharge machining-A potential choice for surface modification of metallic implants for orthopedic applications: A review. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230 (2), 331-353.

Samson, R.M., Sridhar, A., Ranjith, R., Muthiya, S.J., Dhanraj, J.A., Basavankattimath, M.S., & Shata, A.S. (2022). Experimental investigation of heat-treated tool on wire electric discharge machining of titanium alloy (Ti-6Al-4V). Advances in Materials Science and Engineering, 4160276.

Sharma, V.S., Sharma, N., Singh, G., Gupta, M.K., & Singh, G. (2022). Optimization of WEDM Parameters While Machining Biomedical Materials Using EDAS-PSO. Materials, 16, 114.

Sidhu, A., S. (2021). Surface texturing of non-toxic, biocompatible titanium alloys via electro-discharge. Reports in Mechanical Engineering, 2(1), 51–56.

Singh, R.K., Tiwari, S.K., Srivastava, S.C. & Kumar, B. (2023). Hybrid Taguchi-GRA-CRITIC Optimization Method for Multi-Response Optimization of Micro-EDM Drilling Process Parameters. Tehnički vjesnik, 30 (3), 804-814.

Stojković, J.R., Stojković, M., Turudija, R.., Aranđelović, J., & Marinkovic, D. (2023). Adjustable Elasticity of Anatomically Shaped Lattice Bone Scaffold Built by Electron Beam Melting Ti6Al4V Powder. Metals, 13 (9), 1522.

Wang, Y., Wang, Q., Ding, Z., He, D., Xiong, W., Chen, S., & Li, Z. (2018). Study on the mechanism and key technique of ultrasonic vibration and magnetic field complex assisted WEDM-LS thick shape memory alloy workpiece. Journal of Materials Processing Technology, 261, 251-265.

Wang, M., Peng, Z., Li, C., Zhang, J., Wu, J., Wang, F., Li, Y., & Lan, H. (2022). Multi-Scale Structure and Directional Hydrophobicity of Titanium Alloy Surface Using Electrical Discharge. Micromachines, 13(6), 937.

Wasif, M., Iqbal, S.A., Fatima, A., Yaqoob, S., & Tufail, M. (2020). Experimental investigation for the effects of wire EDM process parameters over the tapered cross-sectional workpieces of titanium alloys (Ti6Al-4V). Mechanical Sciences, 11(1), 20211-2032.