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Research Article

Experimental Analysis of Spiral Finishing Process on EDM Drilled Hole in Titanium

Md Farid Hossain,[1] Abhijit Bhowmik ,[1,2] Samim Alam,[3] Sameer Sheshrao Gajghate ,[4] Golam Kibria,[3] Chander Prakash,[5] and Himadri Majumder [4]

[1]*Department of Mechanical Engineering, Dream Institute of Technology, Kolkata 700104, India*
[2]*Chitkara Centre for Research and Development, Chitkara University, Chandigarh, Himachal Pradesh 174103, India*
[3]*Department of Mechanical Engineering, Aliah University, Newtown Campus, Kolkata 700156, India*
[4]*Department of Mechanical Engineering, G H Raisoni College of Engineering and Management, Pune 412207, India*
[5]*Centre of Research Impact and Outreach, Chitkara University, Rajpura 140417, Punjab, India*

Correspondence should be addressed to Himadri Majumder; himu.nita@gmail.com

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It is quite evident that some of the experimental research works have been carried out by researchers in the area of spiral polishing using abrasive for surface finishing improvement but most of the experiment has been employed on Steel or Alloy Steel as a material. Very few number of research works have been performed by researchers across the globe on the Spiral Polishing Method of Titanium holes made by Electrical Discharge Machining (EDM). Therefore, experimental investigations were carried out in the area of Spiral Polishing and Finishing of EDM-drilled holes of various materials to meet the desired goal of demands on the surface quality. This experimentation aims to develop a novel method with spiral polishing using abrasive flow finishing. To explore the search investigation and find out the better surface finishing for through holes made on EDM, the process parameters have been designed using the Taguchi L_{16} orthogonal array with input parameters such as Current (I), Pulse on time (T_{on}), and Pulse off time (T_{off}). The addition of Boron Carbide Powder with Handwash, Glycerine, Shampoo, and Liquid Soap is used to decrease the Surface Roughness (Ra) with a ratio of 5 : 1. The Taguchi technique is used to assess the P/M process parameter setting for a given signal to noise (S/N) ratio.

1. Introduction

Electrical Discharge Machining is a nonconventional machining procedure that involves multiple recurrent electrical discharges of short duration and high current density between the workpiece and the tool [1–3]. Today, EDM is a common machining technique in a variety of industrial facilities across the globe. The majority of standard machining procedures such as drilling, grinding, and milling fail to manufacture geometrically complicated or challenging forms and sizes [4, 5]. For that advancement, EDM has been chosen for drilling on titanium material, and for a better surface finish, abrasive flow finishing process was added further. The main purpose of Abrasive Flow Finishing (AFF) is to deburr, polish, and finish hard-to-reach surfaces and edges by allowing an abrasive-filled polymer to flow from two vertically opposed cylinders [6–9]. The medium (a mixture of viscoelastic material, say, polyborosiloxane, additives, and abrasive particles) enters the workpiece through the tooling [10, 11]. The abrasive particles (SiC, Al_2O_3, CBN, and diamond) penetrate the workpiece surface depending upon the extent of the radial force acting on them. Due to the tangential/axial force, the material is removed in the form of microchips [12–15].

Yan et al. [16] presented research that investigates the spiral polishing technique and micro-finishing device for alloy steel. They did this by employing a slurry of SiC abrasive grains together with polymer, wax, and silicone carrier oil as their machining medium. In addition to the polymer, wax, and silicone oil, abrasive granules of 12, 30, and 150 mm were added to the mixture. The findings indicate that increasing the rotation speed and the amount of machining time during the micro-finishing process resulted in a reduction in the medium viscosity and an improvement in the hole surface roughness. Jain [17] investigated the effect that the parameters of the Abrasive Filming (AFM) process had on the amount of material removed and the surface finish. Modeling and simulation were employed to investigate the mechanics of AFM, which includes abrasive grains making indentations on the surface of the workpiece in order to remove material. In addition to that, the research investigated tangential force, specific energy, and heat transport. Using surface roughness measurement, atomic force, and scanning electron microscopy, Yamaguchi and Shinmura [18] investigated how processing affects the surface texture of a material. They suggested using an internal magnetic abrasive finishing method for manufacturing tubes with highly finished interior surfaces for use in critical applications such as clean gas or liquid piping systems. According to the findings, magnetic abrasive finishing is more effective at removing material than magnetic jig finishing, making it a good choice for surfaces that need a lot of material to be removed. Jha and Jain [19] designed a smart magnetorheological polishing fluid for use in their precision finishing technique for intricate interior geometries. The procedure was validated by conducting tests on workpieces made of stainless steel at varying intensities of the magnetic field. After ending with a zero magnetic field strength, the results indicated no significant change in the surface roughness; nevertheless, the roughness steadily decreased as the magnetic field intensity increased. Kuriyagawa et al. [20] conducted research on an electrorheological fluid-assisted micro-spherical generator system, which is a machine that can both micro-grind and micro-polish. They discovered that grinding first led to better polishing performance for smaller regions. The research also investigated the behavior of abrasive particles and electrorheological particles near the tool tips, and it found that the electrorheological effect makes it easier to gather particles. Jain [21] employed neural networks to model and optimize AFM process parameters. However, they discovered that previous approaches were difficult to process complex surfaces and were sluggish. The abrasive concentration, the mesh size, the number of cycles, and the medium flow speed were the most important process parameters. The greater the number of cycles and the magnification, the more clearly the tool markings may be seen. An investigation into the use of magnetic force for inner wall spiral polishing was carried out by Chen and Yan [22]. They came up with an idea for a container that was hollow and had a spindle attached to a CNC or machining tool. A combination of steel grits, polystyrene balls, silicon oil, and SiC particles was employed as the abrasive in this process. According to the findings of the research, increasing the amount of time spent machining results in improved fluidity of the abrasives, which produces polishing surfaces of a better quality. Patel and Pandey [23] examined a variety of standard and unconventional methods, including laser shock peening, heat treatment, and machining, with an emphasis on material removal and thermal procedures to improve the mechanical characteristics, dimensional accuracy, and quality of metal-based additive manufacturing components. Gong et al. [24] provided a useful solution for micro-hole manufacturing without the need for additional clamping or tool changes by demonstrating via the fabrication of micro-bearing bushings that high machining efficiency, little wear, and no recasting layer are achievable. Abeni et al. [25] analyzed process performances, surface roughness, and burr extension, providing insights into the optimal processing conditions and parameters for postprocessing 3D-printed metal samples, facilitating comparisons and evaluations of machining conditions for enhanced surface quality and dimensional accuracy.

This paper describes the experimentation on the spiral finishing process of EDM-drilled holes on Titanium material using the parametric design of Taguchi's methodology. Tungsten was picked as the material for this study because it is being used in more and more ways to make tools. No spiral finishing operation has been done before with these parameters and titanium holes. The effect of various surface finishing parameters such as speed of rotation of the motor shaft, time of rotation, i.e., finishing time, abrasive concentration, and liquid media on surface roughness has been studied through surface finishing of Titanium holes. The selection of optimum values is essential for the process of surface finishing. The use of spiral finishing to titanium holes is not common, but it highlights the potential for additional developments and surface quality improvements in the area of advanced finishing.

2. Experimental Setup and Procedure

2.1. Material Preparation. A sheet of commercially pure titanium (Ti) measuring 150 mm in length, 85 mm in width, and 3.5 mm in thickness served as the workpiece. The flowchart of the experimental setup is shown in Figure 1. Start by using the Wire-Cut EDM machine to smooth down any sharp edges, and then divide the sheet in half so you can easily hold the tasks in the vice while you drill them. For this experiment, a tungsten rod measuring 35 mm in length and 5 mm. in width and 5 mm in diameter was employed. Figure 2 shows an image of a tungsten cutting tool and a titanium workpiece taken just before EDM machining. The material characteristics of the workpiece are listed in Table 1. When drilling with a high current and short on/off period, the resulting holes have a terrible finish. After many iterations, we finally nailed down the optimal cutting parameter for our material and cutter. We drilled a total of twenty-one holes in the two titanium pieces of the workpiece. Most of the holes were drilled at intervals of around 120 to 180 minutes. Some of the holes required more machining time and had subpar top and bottom surface finishing. Figure 3 is an image showing the titanium substance with holes cut into it. Table 2 displays the characteristics of common hole-cutting tool materials.

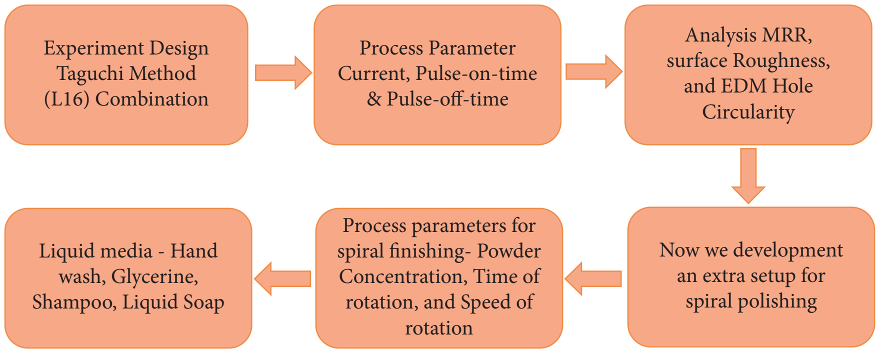
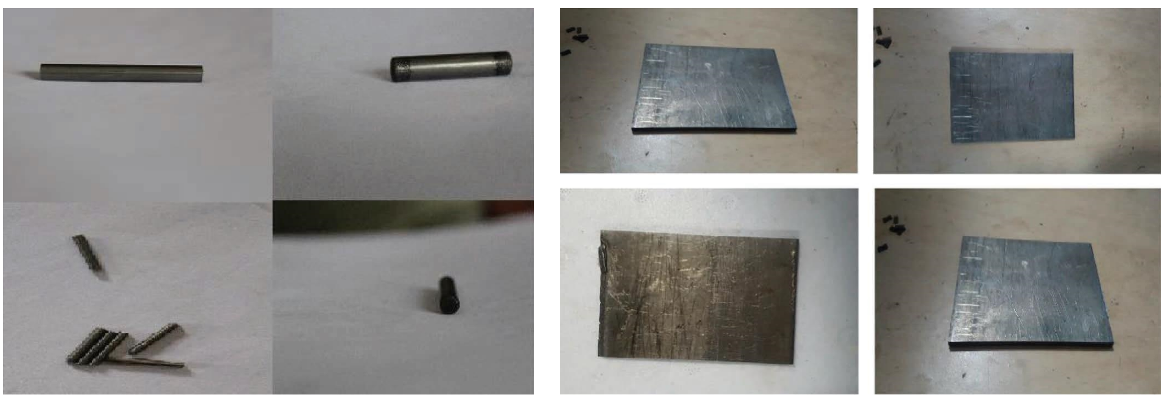


Figure 1: Flowchart of the experimental setup.



(a) (b)

Figure 2: Photographic view of (a) tungsten tool and (b) titanium material before machining in EDM.

Table 1: Properties of workpiece material.

Material (workpiece)	Tensile strength (MPa)	Yield strength (MPa)	Atomic weight	Melting point (°C)	Density (gm/cm^3)
Titanium	210–1380	140	47.88	1725	4.506

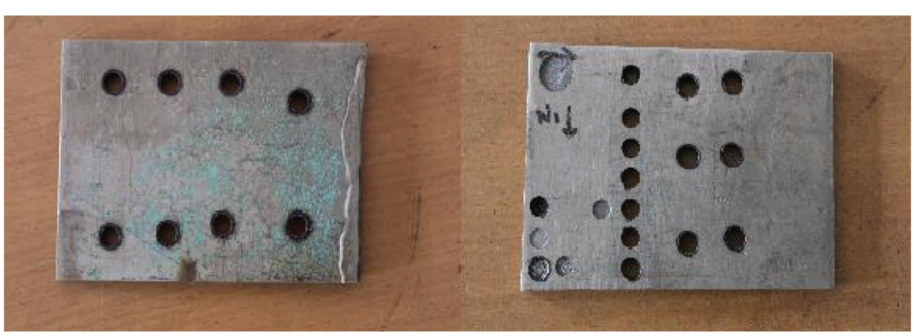


Figure 3: Photographic view of titanium material after making through holes on EDM.

Table 2: Properties of tool material used in hole cutting.

Material (tool for hole cutting)	Tensile strength (MPa)	Yield strength (MPa)	Modulus of elasticity (GPa)	Atomic weight	Melting point (°C)	Density (gm/cm^3)
Tungsten	1725	750	400	183.84	3422	19.3

2.2. Plan of Experiment. The EDM process parameter in this work is mentioned in Table 3. Four different process parameters, namely, Powder Concentration (3, 5, 7, and 9 gm), Time of rotation (1, 2, 3, and 4 min.), Speed of rotation (30, 50, 70, and 90 rpm), Liquid media (Handwash, Glycerine, Shampoo, and Liquid Soap), are selected with their four different levels in this work. A total of 16 experiments done as per Taguchi's L_{16} orthogonal array will be considered in this EDM approach as shown in Table 4.

2.3. Abrasive Finishing Process Setup Development. The primary part of this research is the operation of spiral polishing using abrasive. The angle plate of dimensions of 4″ in length, 7″ in width, and 10 mm in thickness is collected where both the plates are made of iron, to make the fixture for holding the workpiece and tool in a proper manner to carry out the finishing experiment. In this operation, rotate the tool both clockwise and anti-clockwise during the finishing of the through holes' internal surface. That is why we purchased a stepper motor with a digital speed controller and power supply. We used the motor to rotate the tool using various speeds of motor shaft rotation. The features and control of the motor are shown in Figure 4. Then the angel plate is machined in the Shaper Machine to make the surface of the angel plate smooth and also to check that the two sides of the angel plate are exactly perpendicular to each other. The research motto is to get the desired surface finish in operation. For this reason, every step during setup was done very carefully to get the desired precession outcome. After machining the angel plate, we cut a small part of the plate to attach with the angel plate by welding to make the system for holding the motor. For that purpose, a small plate is attached in the middle of the angel plate's one side in such a way that the motor should fit on the plate vertically as shown in Figure 5. After this, using a lathe machine, a hole is made on the attached small plate in the proper position so that the motor shaft can be passed through the hole as shown in Figure 6.

Now four holes are made in the small plate for the screws of the motor to fix it on the plate. Then the motor is screwed with the attached plate so that the motor shaft remains vertically fixed with the motor shaft facing toward the bottom side of the angel plate. Then a drill chuck is attached to the motor shaft to hold the drill bit during rotation while operating surface finishing. The whole system made till this point is shown in Figure 7. Next, during spiral finishing, the fixture for the workpiece material is created. For that, a circular hole on the bottom side of the angel plate, about 5 cm in diameter just below the drill chuck which is connected to the hanging plate, is created. Make this hole because the space gap between the angel plate bottom side and the drill chuck is very small to hold the drill during operation. After making the big hole, easily hold the drill bit in the drill chuck and also pass through the holes of titanium material. The fixture of workpiece material is made so that every hole can be used for finishing. Another plate of the same dimension is taken as the bottom side of the angel plate to fit it on the angel plate for holding the workpiece. A few holes of diameter 5 mm are cut on that plate so that every hole can be used for finishing operation. Four small bushes are made to attach the plate on the bottom side of the angel plate.

Some wooden arrangements are made to mount the arrangements on the wooden structure. Make holes in the wooden structure to fix it with the angel plate in such a manner that the big hole on the bottom side plate remains in between the two wooden pillars. This is made so that the abrasive mixture pot is just beneath the bottom surface of the workpiece material as shown in the figure. Assembling all the parts completes the required setup for this experiment. The complete setup for spiral polishing is shown in Figure 8.

So, the present experiment, according to the concept of spiral polishing with abrasive, designed a set of apparatus onto a steel plate attached to the angel plate. With the help of abrasive and rotating tools, precision spiral polishing can be carried out. The fixed rotating tool is used by the equipment for the micro-abrasive medium with the spiral polishing technique to pick up the abrasive medium along with the rotation. During the operation, the abrasive media make direct contact with the workpiece. Thus, the workpiece surface is cleared of minute pieces and dirt by the abrasive medium. The revolving tool polishes the workpiece surface while spinning at a high speed.

2.4. Abrasive Finishing Process. The experimental setup is prepared to be used for the spiral polishing method. It is made in such a way that the setup is suitable for this type of abrasive finishing process. In this process, a spiral lapping mechanism is applied so that the polishing media flow over the surface to be finished back and forth. Figure 9 shows the mechanism of spiral polishing using the screw.

During the rotation of the screw in its axis, the abrasive medium is taken by a spiral groove provided on the screw surface. In this way, the polishing medium abrades the rough surface, and the finishing process is carried out. The rotation of the screw can be either one direction or CW-CCW type. Due to the spiral movement of working media, the finishing proves to be uniform. Properties of tool material used in spiral polishing are shown in Table 5.

3. Result and Discussion

3.1. EDM Machining Results. After a careful literature survey, several process parameters were taken to carry out the hole-cutting procedure. To eliminate the potential for measurement error caused by oil contamination, samples were dried with hot air after each hole-cutting experiment. The performance of the EDM technique to make these holes was assessed through process performances such as overcut, taper, and tool wear. As mentioned in the preceding section, the material removal rate was determined by comparing the weight of the sample before and after the cutting of holes using high-precision weighing equipment. Similarly, the tool wear rate was determined by comparing the tool's pre- and postmachining weights on a high-precision weighing

Table 3: Details of process parameters and their ranges.

Parameters	Units	Level			
		1	2	3	4
Powder concentration	gm	3	5	7	9
Time of rotation	min	1	2	3	4
Speed of rotation	rpm	30	50	70	90
Liquid media	NA	Handwash	Glycerine	Shampoo	Liquid soap

Table 4: Experimental combination of process parameters for spiral finishing.

Experiment No.	Powder concentration (gm)	Time of rotation (min)	Speed of rotation (rpm)	Liquid media
1	3	1	30	Handwash
2	3	2	50	Glycerine
3	3	3	70	Shampoo
4	3	4	90	Liquid soap
5	5	1	50	Shampoo
6	5	2	30	Liquid soap
7	5	3	90	Handwash
8	5	4	70	Glycerine
9	7	1	70	Liquid soap
10	7	2	90	Shampoo
11	7	3	30	Glycerine
12	7	4	50	Handwash
13	9	1	90	Glycerine
14	9	2	70	Handwash
15	9	3	50	Liquid soap
16	9	4	30	Shampoo

Figure 4: Machining on lathe for making the system for motor holding.

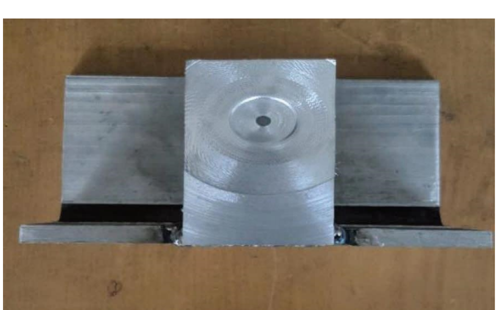


Figure 5: Photographic view of angel plate with attachment for holding motor.

Figure 6: Photographic view of angel plate with motor and drill chuck attachments.

Figure 7: Photographic view of four bushes made for additional plate attachments and drill chuck attachment.

Figure 8: Different angle photographic view of complete setup for spiral.

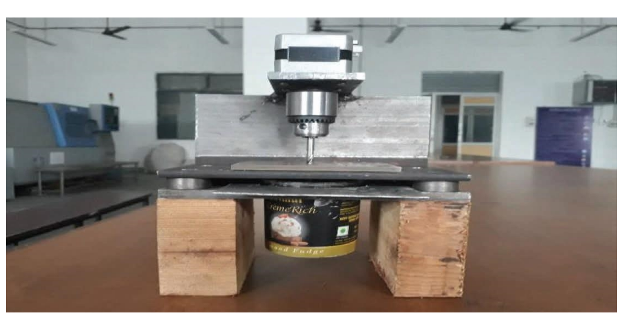


Figure 9: Photographic view of complete setup with abrasive mixture holding system.

machine. Then, using an optical microscope, we determined the amount of overcut by comparing the diameter of the drilled holes in the workpiece to the estimated diameter of the cutting tool. All the trials determined the hole taper using an equation. Information on the results of 16 different experiments is shown in Table 6.

Table 5: Properties of tool material used in spiral polishing.

Material (tool used for spiral finishing)	Yield strength (MPa)	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Thermal conductivity (W/m/°K)	Tensile strength (MPa)
High-speed steel	3250	8138	190–210	0.27–0.30	41.5	415–700

Table 6: Experimental results of EDM process performances.

Sl. No.	Current (A)	T_{on} (μs)	T_{off} (μs)	MRR (mg/min)	TWR (mg/min)	Overcut (mm)	Taper (degree)
1	8	250	200	25.9333	7.8600	0.1300	0.0191
2	9	200	150	25.0083	4.3000	0.1296	0.0177
3	9	250	200	19.9766	6.2600	0.1325	0.0109
4	9	250	200	23.2061	10.0076	0.1226	0.0229
5	9	250	200	24.7415	9.2630	0.1348	0.0206
6	9	250	200	19.9926	5.6866	0.1466	0.0215
7	9	250	200	25.0008	7.1625	0.1313	0.0219
8	7	250	150	34.3700	6.0125	0.1223	0.0167
9	7	200	150	29.3276	7.6266	0.2109	0.0206
10	7	200	250	20.0520	6.4107	0.2045	0.0242
11	10	250	150	20.4605	4.4177	0.2726	0.0219
12	10	250	200	13.6646	6.5060	0.2025	0.0221
13	10	250	200	16.3320	7.2040	0.2204	0.0215
14	10	250	200	17.9162	6.5966	0.1755	0.0231
15	10	250	150	18.7650	6.4606	0.1738	0.0191
16	10	200	200	17.1326	11.1646	0.1762	0.0196

Table 7: Results of circularity measurement of top surface.

Exp. No.	Values before spiral finishing			Values after spiral finishing		
	Area	Perimeter	Circularity	Area	Perimeter	Circularity
1	303034	2017.027	0.9360	140777	1343.835	0.9796
2	282304	1900.658	0.9826	254678	1795.430	0.9928
3	286748	1905.857	0.9920	251991	1787.998	0.9905
4	306419	2061.297	0.9062	244855	1765.039	0.9876
5	299091	2008.345	0.9392	263805	1830.240	0.9896
6	291851	2007.529	0.9100	255409	1799.610	0.9910
7	334031	2072.157	0.9775	259789	1814.788	0.9912
8	436672	2358.368	0.9866	243294	1759.362	0.9877
9	445264	2378.647	0.9889	243497	1757.476	0.9906
10	407720	2289.806	0.9771	238237	1737.960	0.9911
11	416094	2322.562	0.9693	259160	1809.731	0.9943
12	439201	2367.026	0.9850	248502	1775.177	0.9909
13	421933	2327.462	0.9787	224930	1688.161	0.9918
14	441310	2388.830	0.9718	254043	1792.892	0.9931
15	434734	2356.201	0.9840	257817	1807.260	0.9919
16	459431	2450.423	0.9614	257852	1807.659	0.9916

3.2. Spiral Finishing Process. The machined holes that are generated in the EDM process are finished by the spiral finishing process. Before conducting the spiral finishing process, the circularity of each hole was examined by measuring the area and perimeter of the hole. These values of the area and perimeter of the hole were taken from the microscopic images of holes. After the experimentation of spiral finishing, again, the circularity of each hole was measured by the same procedure. For measuring the circularity, the image processing software ImageJ Version 1.44 was used. The value of the circularity of the hole indicates the quality of the hole. Holes having circularity value 1 indicate the hole to be ideally circular. The measured circularity value for the holes before and after spiral finishing is given in Tables 7 and 8 for the top and bottom surfaces. The result of the percentage of improvement of circularity is shown in Table 9.

After the experimentation of spiral finishing, again, the internal wall surface roughness of each hole was measured by a surface texture measuring instrument. Surface roughness, often shortened to roughness, is a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. In surface metrology, roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface.

Table 8: Results of circularity measurement of the bottom surface.

Exp. No.	Values before spiral finishing			Values after spiral finishing		
	Area	Perimeter	Circularity	Area	Perimeter	Circularity
1	110565	1375.912	0.9339	285641	1902.025	0.9729
2	262108	1828.790	0.9848	286190	1902.756	0.9933
3	220102	1723.590	0.9310	283945	1894.942	0.9936
4	240779	1778.483	0.9565	289656	1915.695	0.9918
5	254697	1804.525	0.9828	285296	1900.105	0.9930
6	259701	1817.366	0.9880	280880	1884.712	0.9936
7	191227	1658.427	0.8737	287188	1908.965	0.9903
8	255349	1804.522	0.9854	305321	1969.972	0.9886
9	256168	1812.258	0.9801	289077	1916.886	0.9886
10	245589	1783.682	0.9700	234021	1726.272	0.9868
11	249559	1854.065	0.9122	366619	2158.911	0.9884
12	243351	1783.605	0.9612	331091	2052.368	0.9877
13	252409	1856.554	0.9202	302799	1968.488	0.9819
14	253906	1806.188	0.9780	253417	1791.545	0.9921
15	252409	1790.781	0.9890	258512	1807.508	0.9943
16	252146	1802.513	0.9752	258580	1808.071	0.9939

However, in practice, it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose. Ra is measured for the hole surface which is the arithmetical average value of all absolute distances of the roughness profile from the center line within the measuring length. The measured values of surface roughness are shown in Table 10.

3.3. Analysis of Results of Spiral Finishing Process. After conducting the spiral finishing process of all 16 experiments designed using the Taguchi methodology, the results of circularity and surface roughness were analyzed by using graphical plots obtained in Minitab software (version 18). These plots are discussed here under.

3.3.1. Results and Discussion on Top Hole Circularity. Figure 10 shows the graphical representation of the main effect plot for S/N ratios of top-hole circularity. The graph is created with the help of Minitab software using different values of the four parameters, i.e., Powder concentration, Time of rotation, Speed of rotation, and Liquid media, with respect to the percentage improvement of top hole circularity. From the plot, it is seen that the circularity of holes improves when the powder concentration values are 5 and 9. On the other hand, the circularity improvement is low while the powder concentration value is 3; also, taking the value 7, it gives the least improvement of hole circularity. Coming to the next parameter, i.e., time of rotation, the graph clearly shows that the circularity is achieved while the finishing time of rotation is 2 minutes. Taking 1 minute time of rotation, the circularity improves but when the time of rotation during spiral finishing is 3 or 4 minutes, it gives less improvement in circularity. That means a better finishing result can be achieved with less time for finishing operation. In the case of speed of rotation during spiral finishing, it is observed from the graph that the speed of rotation plays an

Table 9: Results of improvement of hole circularity.

Exp. No.	Percentage improvement	
	Top surface	Bottom surface
1	4.66	4.18
2	1.04	0.86
3	0.03	6.72
4	8.98	3.69
5	5.37	1.04
6	9.01	0.57
7	1.40	13.35
8	0.11	0.32
9	0.17	0.87
10	1.43	1.73
11	2.58	8.35
12	0.60	2.76
13	1.34	6.71
14	2.19	1.44
15	0.80	0.54
16	3.14	1.92

Table 10: Results of surface roughness.

Hole No.	Surface roughness (Ra)
H1	1.5533
H2	1.7400
H3	1.5600
H4	1.9670
H5	1.4800
H6	1.5600
H7	0.4133
H8	1.2466
H9	1.1416
H10	1.3666
H11	1.3466
H12	0.9733
H13	1.8533
H14	1.8800
H15	2.6533
H16	2.2144

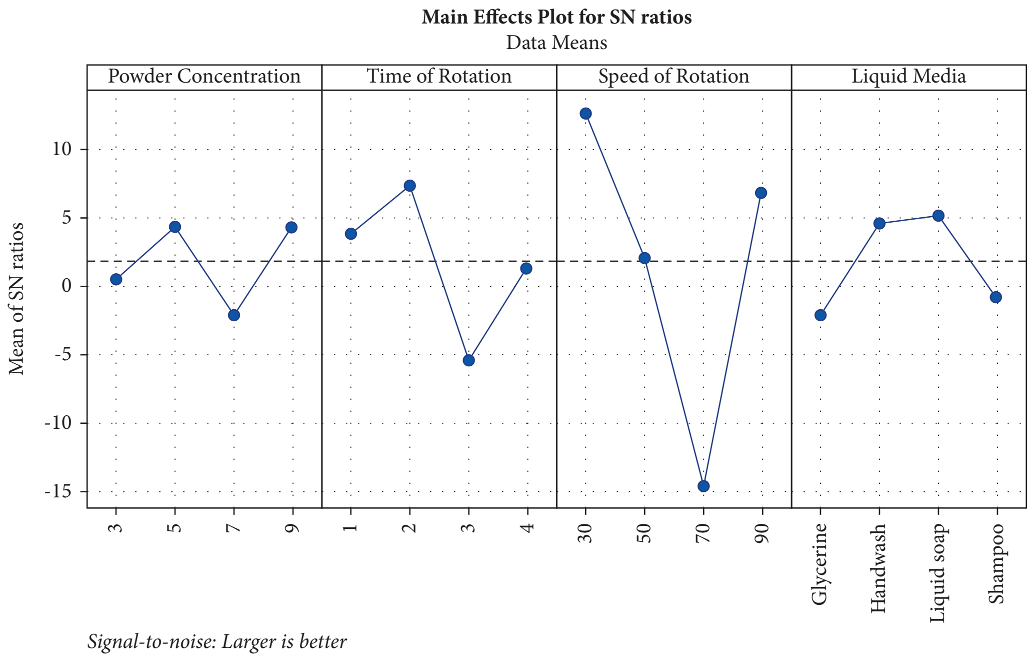


FIGURE 10: S/N ratio plot of top hole circularity.

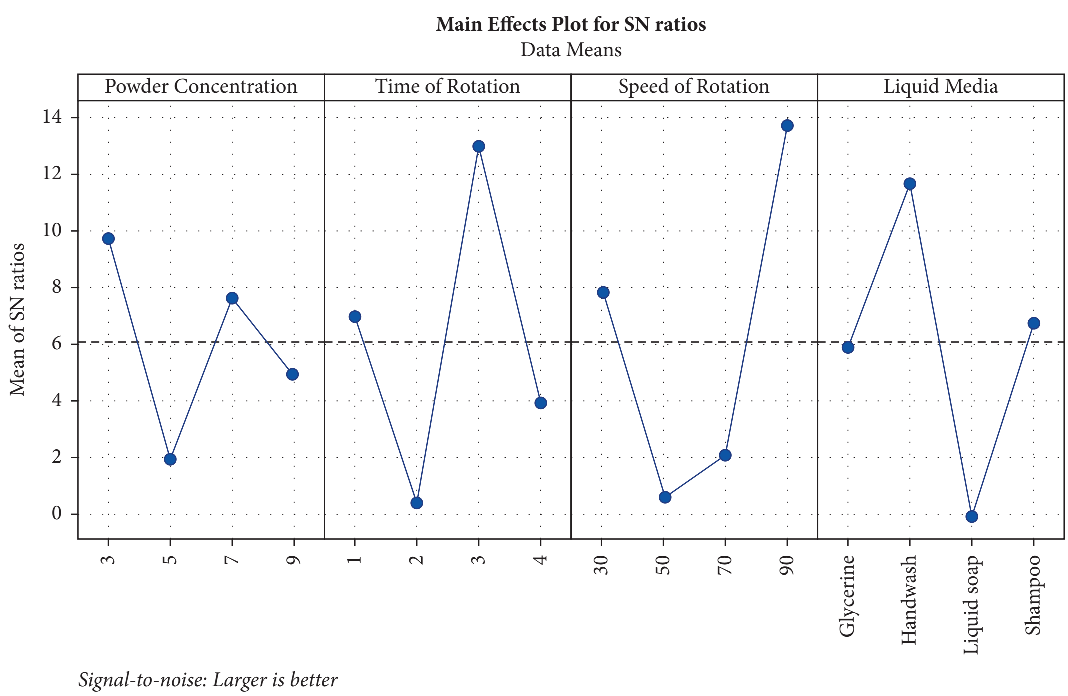


FIGURE 11: S/N ratio plot of bottom hole circularity.

important role in spiral finishing operation. As the values of speed of rotation are taken at 30, 50, or 90 rpm, the circularity of holes get improved after spiral finishing. The result has been achieved while taking the value of 30 rpm for rotation speed. But taking a speed of rotation value of 70 gives the least improvement in finishing result among all the experiments. For liquid media, the plot shows that improvement of hole circularity is achieved when the liquid medium for the abrasive mixture is made with handwash and liquid soap. In the case of liquid soap, the result is achieved. Taking glycerine and shampoo as liquid media has less effect on circularity improvements of holes.

The top hole circularity result may be obtained by merging these four plots, which suggests that the four finishing operation factors have varying impacts on the improvement of hole surface quality. The circularity can be achieved by taking these values of parameters as powder concentration of 5 gm, time of rotation of

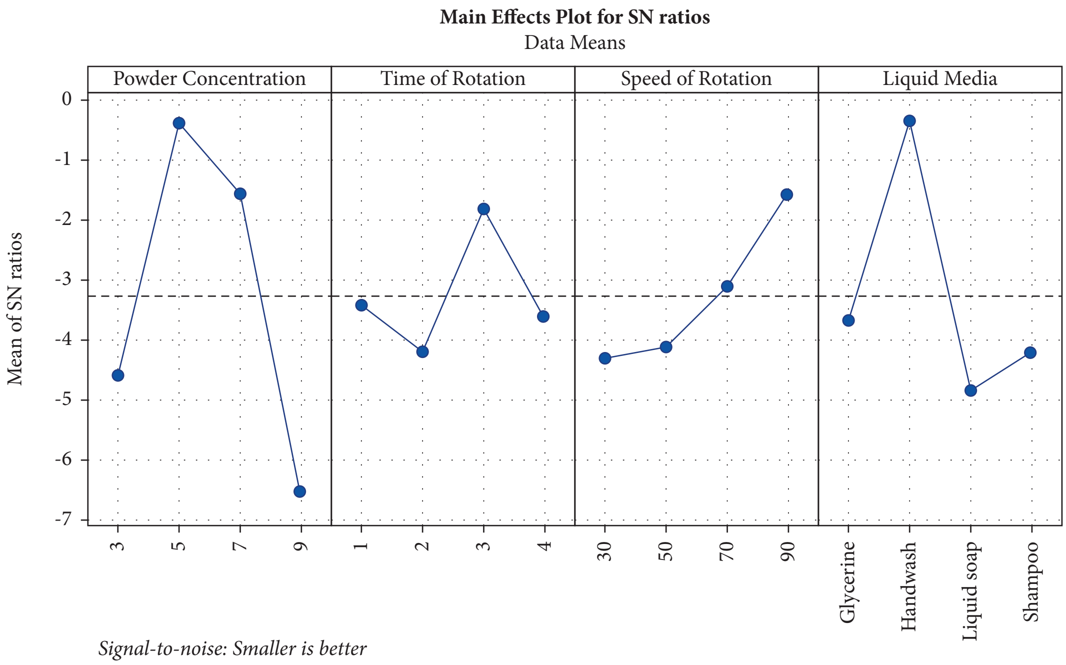


Figure 12: S/N ratio plot of surface roughness.

2 minutes, speed of rotation of 30 rpm, and liquid media as liquid soap. This is the result of the improvement of the top surface of the holes.

3.3.2. Results and Discussion on Bottom Hole Circularity. Figure 11 shows the graphical representation of the main effect plot for S/N ratios of bottom-hole circularity. The graph is also created with the help of Minitab software using different values of the four parameters, i.e., powder concentration, time of rotation, speed of rotation, and liquid media, with respect to the percentage improvement of bottom hole circularity. From the plot, it is seen that the circularity of holes improves when the powder concentration values are 3 and 7. On the other hand, the circularity improvement is low while the powder concentration value is 9; also, taking the value 5, it gives the least improvement of hole circularity. Coming to the next parameter, i.e., time of rotation, the graph clearly shows that the circularity is achieved while the finishing time of rotation is 3 minutes. Taking 1 minute time of rotation, the circularity improves but when the time of rotation during spiral finishing is 2 or 4 minutes, it gives less improvement in circularity. Especially when the time of rotation is taken as 2 minutes, the graph shows very little improvement of bottom hole circularity. In the case of speed of rotation during spiral finishing, it is observed from the graph that the speed of rotation plays an important role in spiral finishing operation. When the values of speed of rotation are 30 or 90 rpm, the circularity of holes improved after spiral finishing. The result among all the experiments has been achieved while taking the value of 90 rpm for rotation speed. But taking a speed of rotation value of 50 or 70 rpm gives less improvement in the finishing result. For liquid media, the plot shows that improvement of hole circularity is achieved when the liquid medium for the abrasive mixture is made with handwash, glycerine, and shampoo. In the case of liquid soap, the lowest quality of surface finishing is achieved. Taking liquid soap as liquid media, it has very little effect on circularity improvements of bottom holes.

The combination of these four plots yields a bottom-hole circularity result, indicating that the four finishing operation factors influence hole surface quality improvement to varying degrees. The circularity can be achieved by taking these values of parameters as powder concentration of 3 gm, time of rotation of 3 minutes, speed of rotation of 90 rpm, and liquid media as handwash. This is the result of the improvement of the bottom surface of holes.

3.3.3. Results and Discussion on Surface Roughness. Figure 12 shows the graphical representation of the main effect plot for S/N ratios of surface roughness. The graph is also created with the help of Minitab software using different values of the four parameters, i.e., Powder concentration, Time of rotation, Speed of rotation, and Liquid media, with respect to the surface roughness of the internal wall of Titanium holes. From the plot, it is seen that the surface roughness of holes improves when the powder concentration values are 5 and 7. On the other hand, the surface roughness improvement is low while the powder concentration value is 3; also, taking the value 9, it gives the least improvement of roughness (Ra). Coming to the next parameter, i.e., time of rotation, the graph clearly shows that the surface roughness is achieved while the finishing time of rotation is 3 minutes. Taking 1 minute and 4 minutes of rotation, the roughness is not so improved but when the time of rotation during spiral finishing is 2 minutes, it gives the lowest improvement in surface

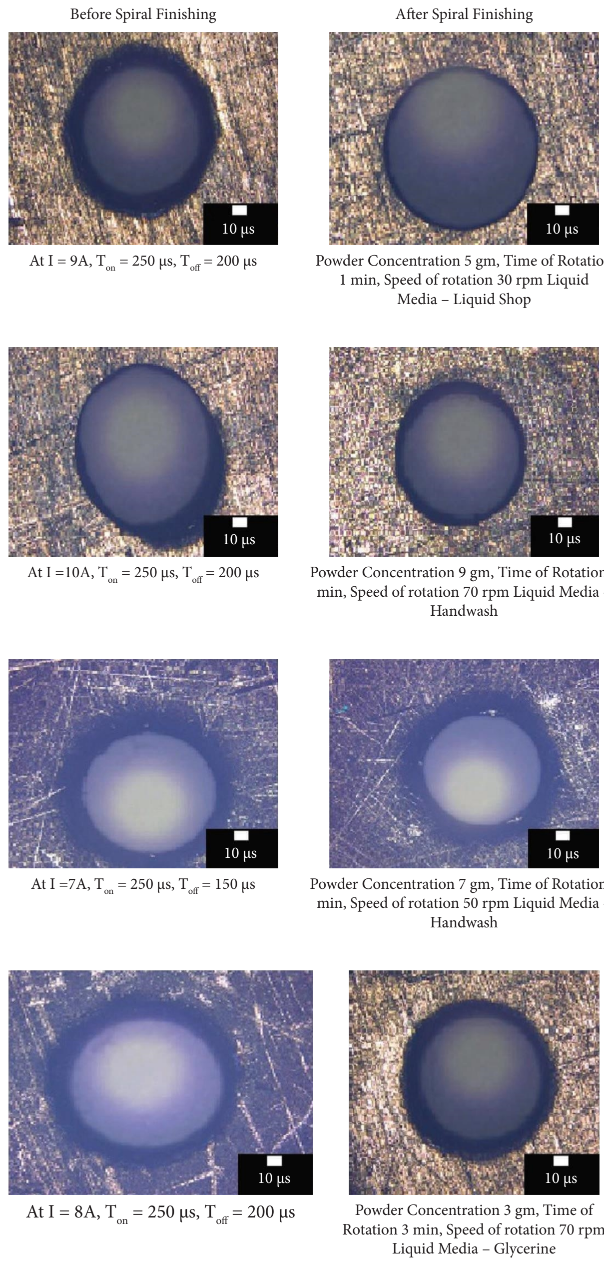


Figure 13: Optical photograph of holes before and after spiral finishing at different parameter settings.

roughness. In the case of speed of rotation during spiral finishing, it is observed from the graph that the speed of rotation plays an important role in spiral finishing operation as concerned with surface roughness values. As the values of speed of rotation are taken at 70 or 90 rpm, the roughness of holes improves after spiral finishing. The result among all the experiments has been achieved while taking the value of 90 rpm for rotation speed. The rotational speed value of 30 or 50 rpm gives less improvement in the finishing result. For liquid media, the plot shows that improvement of surface roughness is achieved when the liquid medium for the abrasive mixture is made with handwash. In the case of liquid soap, the lowest quality of surface finishing is achieved. Glycerine and shampoo as liquid media have average effects on surface roughness.

By combining these four plots, it can be concluded that for roughness values (Ra), the four parameters of the finishing operation have more or less effects on hole surface quality improvement. The surface roughness of this spiral finishing can be achieved by taking these values of parameters as powder concentration of 5 gm, time of rotation of 3 minutes, speed of rotation of 90 rpm, and liquid media as handwash. This is the result of the improvement of surface roughness.

3.3.4. Analysis of Microscopic Images of Finished Holes. Using an optical measuring microscope as shown in Figure 13, images of the hole at the top surface and bottom surface were taken for all experiments and the quality of the holes was compared using different images.

In Figure 13, the quality of holes machined by EDM is compared while machining at different parameter settings. By observing these images, it is clear that by proper controlling of process parameters, high-quality holes can be achieved during EDM drilling of titanium material. In addition, the images of the identical holes taken before and after spiral polishing are compared. The results indicate that improved surface finishing of the inside walls of holes may be obtained by using spiral polishing at different rotational speeds and with lower powder concentrations. In Figure 13, from the microscopic photograph of holes before and after spiral finishing at different finishing parameters, it can be observed that the internal surface of holes has been improved in terms of surface quality after spiral polishing.

4. Conclusions and Future Work

This investigation uses an abrasive medium applied to a microlapping surface to examine the machining properties of the spiral finishing technique. The following findings are supported by the developing experimental evidence:

(a) When the current, Ton, and Toff are all higher, the hole-cutting on the material has a very rough finish. Even so, it can make a hole with a melted surface on the object.

(b) A smooth surface (Ra) was achieved by determining the optimal parameter values. One possible option to establish the parameters for the process conditions utilized in the research is to use handwash as the liquid medium, with a powder content of 5 gm, a rotation period of 3 minutes, and a rotation speed of 90 rpm.

(c) Experiments were done to find out the speed of the motor shaft's movement, the time it takes for the shaft to turn, the amount of grit in the medium, and the type of medium (liquid or solid) that affected circularity. The circularity for bottom surface holes can be achieved by setting the parameters to 3 g powder content, 3 minutes of spin, 90 rpm rotation speed, and handwash as the liquid medium. You can make the holes on the top surface round by setting the powder content to 5 g, the time of rotation to 2 minutes, the speed of rotation to 30 rpm, and the liquid medium to liquid soap.

(d) Utilizing the signal-to-noise ratio (SNR) analysis, determine the ideal parameter combination that maximizes circularity and minimizes Ra.

5. Future Work

(a) Exploit innovative optimization techniques to improve spiral finishing on titanium EDM-drilled holes for better surface quality and faster machining.

(b) Analyze titanium's specific features to optimize spiral finishing process settings for material hardness and thermal conductivity.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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