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Performance Evaluation of WEDM process of EN 31 using Multiple Electrode Material

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EDM is a thermal erosive advanced machining process used to erode material through many small-duration, periodic electrical discharges and large current densities between the workpiece and wire. In the present research work, an effort is made to evaluate the performance of Wire-Electrical Discharge Machining (W-EDM) by machining EN 31 steel using different electrode wires, namely Copper and Brass. EN 31 has good mechanical and corrosive properties, so they are widely used in various fields such as automobile, aerospace, agriculture tool etc. Experiments were designed with the help of Taguchi by considering the parameters such as Electrode type (Copper and Brass), Discharge Current, T_{on} and T_{off}. Experiments have been conducted to optimize the WEDM machining parameters in order to achieve the maximum MRR with minimum SR. It has been found that electrode material and discharge current were the significant factors affecting MRR and SR, respectively. Study shows that brass electrode has a higher MRR when compared with the copper electrode material.

Keywords: Wire-Electrical Discharge Machining (W-EDM), Copper, Brass, Electrode, EN 31, MRR, SR, SN Ratio, ANOVA

1 Introduction

Electrical Discharge Machining (EDM) is an advanced thermal erosion method[1-2] used to extract material through a higher spark frequency, repetitive electrical discharges and high current between the wire as a tool electrode and workpiece which is connected to an anode that is positive terminal as shown in Fig. 1. The removal of material in EDM is based on the erosion of electric sparks taking place amid two electrodes. There are numerous theories in an attempt[3] to clarify the complicated phenomenon of erosive spark[3] It has now been recognized worldwide as the best machining process for the production of forming tools to generate plastics moulding, die casting, forging die, machining for heat-treated tool steel, super alloy, ceramic, and Metal Matrix Composite (MMC) requiring high exactness, complicated shapes with high SR etc., because of its unique machining characteristics and high precision and sustainability[4-7] Industries such as automobile, aircraft, power plants (nuclear reactors), etc. are comparatively more technically sophisticated than other industries such as metal grinding, steel rolling mills and paper processing, etc. Furthermore, in such sectors, there are stringent requirements for consumers and suppliers to adopt closed dimensional accuracy, precise precision and continuous, long-term, effective output of products. As a result, there is always a high demand for advanced materials (like high-temperature resistant alloys with high strengths, e.g. tungsten carbide) and advanced techniques for their machining in such industries. Material science researchers are still flourishing to attain the greatest strength, stiffness, durability and other versatile properties across these advanced materials. Discovery and manufacturing of such kinds of specialized materials is now a huge field of study and is currently growing our awareness of the implementation of colourful technology to obtain the required properties in the substance according to our needs. This work-hardening trend is normal and happens so long as the material is continually machined. And in the case of materials such as tungsten, titanium, high-speed stainless steel, fibre-reinforced composites, satellites, ceramics, cermets and nimonics[8], metal tools are almost difficult to create complicated or even plain forms on them. Many much sought-after specifications about the implementations of these advanced machining processes are the manufacture of non-circular (such as elliptical holes[9], micro-sized, wide aspect ratio, narrow angled entrance, and single or a

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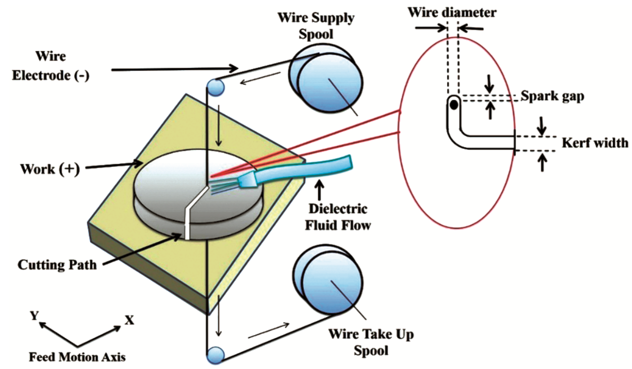

Fig. 1 — EDM Process discharge and material removal.

cluster of holes inside a workpiece. Contoured holes and burr less holes may
also be made by means of specialized machining methods in hard-to-machine products. Such advanced process machining or non-conventional methods are built over a long period of time [10]. These processes are different from conventional ones in such a way that they directly use energy to erode material from the workpiece. Creation of cooling vents in a turbine blade by process of electrical discharge], which is impossible with any conventional machining process[11]. On the other hand, through non-traditional methods, these tight tolerances and higher levels of accuracy can be easily obtained by using EDM. In the EDM process, a voltage difference across the wire and the workpiece is applied. Both the tool and the material at work must be electrical conductors. Both the piece of work and the tool are immersed in a widely used dielectric fluid: EDM oil, kerosene and deionized water[12]. The workpiece is generally made of the anode, and the tool is made of the cathode. The free electrons on the wire as a tool is subjected to electrostatic forces as the electric field is established between the wire and the workpiece. If the electrons work or bonding energy is weak, electrons will emit from the device (assuming it is attached to the negative terminal). These electron emissions are called cold emissions. Such a collision can result in dielectric molecule ionization depending on the role of the dielectric molecule's work or ionization energy and the electron's energy. Consequently, as electrons accelerate, large positive ions and electrons will be produced because of collisions. This cyclic cycle increase density of electrons and ions between the wire as an electrode and the work at the spark gap in the dielectric material. The intensity would be so high that it might characterize the matter in that channel as plasma[13]. This plasma channel will have rather less electrical resistance. And immediately, a huge number of electrons will flow from the tool electrode to the work, and ions will flow from the work to the wire tool. That is called electron avalanche motion. Such motion of electrons and ions is observed as a spark. Thus the electric power is dissipated as the spark's heat energy. The rapid electrons then impinge upon the job and the wire tool's ions. The electrons and ions' kinetic energy in contact with the job and device surface will be transformed into thermal energy, respectively. Such extreme concentrated thermal energy contributes to extreme restricted instant temperature rises, which would surpass $10{,}000^0$ C. EDM process has been presented from a positive perspective, but the method also has some inherent problems associated with it, which require close attention and study studies to achieve the desired and efficient critical yield in WEDM machining products or parts[14]. There are a large number of parameters that directly affect the features of the WEDM process criteria, such as MRR, SR, overcut, as well as another dimensional accuracy. WEDM device manufacturers and users also plan to achieve high machining productivity with optimal accuracy and finish that depends solely on the nature of the job. Therefore, there is obviously a need for systematic synthesis and the categorical quest for parametric settings to achieve efficiency. Various advances in EDM have been reported by researchers involving various dielectric mediums[15-18]. Dry wire EDM was a variation of oil wire EDM machining in that dielectric is exchanged by the gaseous state dielectric form. High-speed gas flows through the device electrode through the in-between electrode gap and is replaced with dielectric fluid. The high-speed gas flow through the gap enables the removal of debris and avoids unnecessary heating of the device and the workpiece at the discharge points. The provision of rotation or planetary motion to the device was found to be necessary for maintaining the stability of the dry-EDM operation. Water is a substitute for hydrocarbon oil as just a dielectric, and that is taken because hydrocarbon-based oils such as kerosene can decompose and emit toxic vapours (CO and CH4). EDM using distilled water culminated in greater MRR with smaller wear of tool than using kerosene, when a spectrum of higher pulse-based energy was used. EDM in water with additives is the improvement of EDM in water; this technique is used to enhance water efficiency. Several kinds of research show the possibility of incorporating organic compounds of glycol such as ethylene, sucrose, polyethene 200,

polyethene 400, polyethene 600, and dextrose to boost the efficiency of deionized water. Spinning the workpiece is a method in which the rotating motion of the workpiece is used to increase the flushing of the dielectric, which ultimately enhances the efficiency of the EDM [19]. Rotating Electrode EDM, the efficiency calculation of the EDM method also improves by adding the rotary type motion of the electrode as it serves as an efficient valve technique of flushing that greatly enhances the MRR and enhances the surface feature.

EDM can cut any material that carries electricity like Inconel[20-21], Titanium[22], Hastelloy, Carbide and more regardless of its strength and toughness. CNC can define any desired contour, such as splines, gears, long thin slots, etc., to be cut via EDM[23]. Multiple sheets of designated material can be cut from one wire pass by piling and welding together[24]. A small workforce is required to prepare bar stock, plates and round stock. May cut hardened or unhardened steel, may cut before or after heat treatment, hardness of the component does not impair the speed or strength of wire cutting, no-contact and no-force operation (appropriate for producing delicate or fragile pieces that cannot endure the tension of conventional machining), can cut thin sheets of 0.002 inches, an excellent alternative for the manufacture of small, highly complex products that would be appropriate for manufacturing. Reduces secondary contour grinding, deburring and polishing operations and thereby produces cost savings, reducing the possibility of scrapping a problematic or costly component due to breakage of the equipment. Production is rapid because, in most cases, little to no equipment and installation is needed, so the quick distribution of parts reduces the total manufacturing period by 37%, but the processing period is reduced by 66%. Complex 3D programming schemes, when cutting with CNC 5-axis WEDM, allow for separate control of the top and bottom contours[25-26]. The extensive literature survey published in this research work discusses various techniques that could have been employed by traditional EDM and WEDM processes by different study groups around the globe in the field of different machining materials. The report also highlights a few interesting works in the field of EDM machining of various materials in order to achieve a good surface finish, minimum kerf width, etc. From the literature review, it is known that there is still room for work to improve process parameters to achieve a reasonable surface finish along with minimum kerf width and a higher removal rate of content.

A comprehensive literature survey was conducted on the impact on the process parameters of the EDM processing response performance of different materials ranging from Aluminum, a ductile material, to a very hard material such as ceramics. Low productivity is a major weakness of the EDM-based process. In the EDM process, the time to accomplish the necessary machining is higher than in the traditional machining phase. All research works reported in the past follow the same objectives of ensuring more effective removal of waste. In order to improve the modification of the EDM cycle, there seems to be a need for more work participation, which will provide better economic MRR with better surface integrity. Present analysis work focuses on crucial elements of EDM's economic efficiency (i.e. cost savings and surface quality improvement) by using the appropriate selection of parameters. The objective of the present investigation is to study the effects of process parameters on performance measures of the different tool electrode materials on the basis of MRR and SR of the machined surface. In this research, therefore, it was proposed to inspect the effect of EDM process parameters on response parameters such as MRR and SR to optimize these input parameters through optimization techniques. The performance of the two dissimilar electrodes (Brass and Copper) is also evaluated in terms of MRR and SR in the current research work.

2 Materials and Methods

With the aid of servo control, a constant gap is established between the device and the workpiece, as shown in Fig. 1 and 2. Figure 1 shows the schematic view of the CNC Wire Cut Electric Discharge Machining (CNC WEDM) process. Experiments are conducted using the CNC Wire Cut EDM (Sprintcut) system, as shown in Fig. 2. Table 1 displays the

Fig. 2 — Experimental Setup – photographic view of CNC Wire – cut EDM

Table 1 — Design factors and their levels

Symbols	Control Factors	Levels			Units
A	Electrode	Copper		Brass	
B	Discharge Current	8	12	16	A
C	Pulse ON Time	25	45	65	µs
D	Pulse OFF Time	20	32	44	µs

Table 2 — Shows Experimental Details

Working Parameters	Description
Workpiece Material	EN 31(HCS)
Size of Workpiece	100×100×12 mm
Electrode Wire Material	Copper, Brass
Polarity of Electrode	Positive
Dielectric	Deionized Water
Dielectric Voltage	110V

Table 3 — Chemical Composition of EN 31

Material	Carbon	Manganese	Chromium	Silicon	Iron
Composition	1.00%	0.50%	1.40%	0.20%	96.90%

Table 4 — Mechanical Properties of EN 31

Properties	Value
Thermal Conductivity (W/mK)	46.6
Density (gm/cc)	7.8
Electrical Resistivity (ohm-cm)	0.0000218
Specific Heat Capacity (J/gm^{0}C)	0.475

experimental details of the wire-cut EDM machine. In the experimental study, Mixed Level Design for four factors, 2 Levels for 1 factor and 3 Levels for 3 Factors each are used, So L18 orthogonal array is selected for this experimental design. The complete design with a description of factors and their levels is shown in Table 2. High Carbon Steel (EN 31) PLATE tool steel. The size of the specimen, 100 mm × 100 mm × 12 mm, was used as a workpiece material for the current experiments. The chemical compositions with mechanical properties of the workpiece components are seen in Table 3 and Table 4, respectively.

Machining was done with multiple electrodes such as copper and brass, different wire materials of size 0.25 mm in diameter. EN 31 High Carbon Steel is machined using EDM-based wire from SPRINTCUT CNC. External flushing flushes the eroded particles away from the sparkling zone. The calculation of the Material Removal Rate is done by the Weight loss method, and the SR is measured by the instrument Surface Roughness Tester. The MRR is proportional to the current, but it is inversely proportional to the pulse duration due to the reduction of the spark efficiency resulting in carbon deposition from the dielectric breakdown. So MRR is measured by weighing specimens before and after machining.

$$\text{MRR}\ \left(\text{mm}^3\ /\ \text{min}\right) = \frac{W_i - W_f}{7.8 \times\ t} \times 100 \quad \ldots(1)$$

Where We, W_{elf} are weight of specimen before as well as after EDM, t represents machining time, and density of steel EN 31 is 7.8 g/cm^3.

SR is a function of the surface texture. The Pocket Surf Gauge is a compact battery-powered device for testing surface roughness with calculated values reflected on a digital readout. Design of experiments (DOE) is the preparation of any investigation procedure where variability is possible, whether under the direct supervision of the experimenter or not. The science of mathematical model architecture emerged from the work of Sir Ronald Fisher in England in the 1920s. Fisher developed the fundamental theory of experimental design and the related data-analysis methodology called Variance of Analysis (ANOVA) during his attempts to increase the yield of agricultural crops. ANOVA is the mathematical method most widely used for the outcomes of the tests when evaluating the percent contribution of each parameter to the degree of trust displayed. The study using ANOVA for a specified situation helps to conclude which parameter needs to be controlled.

Taguchi's Approach makes extensive use of orthogonal arrays. The Taguchi process includes reducing deviation in the process by the robust design of experiments. Taguchi highly suggests for repeated runs the use of (S/N) ratio for a similar procedure in the process. The (S/N) ratio is of concurrent consistency measure related to the loss function. The results of the selected WEDM parameters on selected output characters were explored in the key results plots based on data achieved. The optimum state for each of the quality features has been established by means of (S/N) data analysis. Taguchi describes the lack of quality by its 'lack-function.' It blends financial loss with practical definition via a quadratic ally relationship arising from the Taylor series of expansion.

L = loss in an economic unit can be expressed as,

$$L(y) = k(y-m)^2 \quad \dots(2)$$

Where k = constant, which depends on the magnitude of feature with the monetary unit,
m = Characteristic set value,
y = Actual value of the characteristic.

Targeted value at which characteristic the equation is written:

$$L(y) = k(MSD) \quad \dots(3)$$

MSD = Mean Square of deviation

Since MSD represents the mean squares of all deviation from the targeted value instead of the mean value of Taguchi, as loss function has been converted into a parallel equation known as the S/N ratio and incorporates both mean output characteristics with variation about this mean as a single metric. The (S/N) ratios consolidate repetitiveness (minimum two data points needed) as a single value. The high(S/N) ratio given by equations no. 4, 6 and 8 suggests an equilibrium output value with limited variance based on the type of response.

Higher the better (HB)

$$(S/N)_{HB} = -10\log(MSD)_{HB} \quad \dots(4)$$

$$(MSD)_{HB} = \frac{1}{2}\sum_{j=1}^{R} \left(\frac{12}{yj}\right) \quad \dots(5)$$

Lower the better (LB):

$$(S/N)_{LB} = -10\, log(MSD)_{LB} \quad \dots(6)$$

$$(MSD)_{LB} = \frac{1}{R\sum_{j=1}^{R} y_{21}} \quad \dots(7)$$

Nominal the best (NB):

$$(S/N)_{NB} = -10\, log(MSD)_{NB} \quad \dots(8)$$

$$(MSD)_{NB} = \frac{1}{R}\sum_{j=1}^{R} (y_i - y_o)^2 \quad \dots(9)$$

Where R = Repetition numbers.

The goal value for the smaller form is zero. The plot for average response at-parameter level points to the pattern. This is a pictorial way of reacting effects of the parameter. The (S/N) ratio can be viewed as the response of the experimentation test, which evaluates for variance in the test when noise factors are present.

3 Results and Discussion

Table 5 shows the MRR and SR for all the combinations of experiments. The S/N ratios and means of experiments for MRR are given in Table 6 and Table 7, respectively. Table 8 and Table 9 show the S/N ratios and means of experiments for SR, respectively. Taguchi Analysis for MRR shows that the Pulse ON Time is the noteworthy parameter followed by the Electrode material, Discharge Current, then Pulse OFF Time as shown in the

Table 5 — Orthogonal Array for L18

Electrode A	Discharge Current B	Pulse ON Time C	Pulse OFF Time D	MMR	SR
Copper	8	25	20	24.504	2.02
Copper	8	45	32	29.405	2.46
Copper	8	65	44	32.421	3.09
Copper	12	25	20	23.373	2.46
Copper	12	45	32	28.651	3.02
Copper	12	65	44	32.044	4.41
Copper	16	25	32	22.242	3.14
Copper	16	45	44	26.766	4.46
Copper	16	65	20	30.913	5.04
Brass	8	25	44	32.044	1.75
Brass	8	45	20	36.945	1.83
Brass	8	65	32	41.092	2.12
Brass	12	25	32	31.29	2.05
Brass	12	45	44	36.568	2.26
Brass	12	65	20	39.584	2.58
Brass	16	25	44	30.536	2.51
Brass	16	45	20	35.814	3.13
Brass	16	65	32	38.076	4.27

Table 6 — Response Table for Signal to Noise Ratios (Larger is better):

Level	Electrode	Discharge Current	Pulse ON Time	Pulse OFF Time
1	28.81	30.19	28.64	29.89
2	31.03	29.96	30.13	29.88
3		29.61	31.00	29.99
Delta	2.22	0.57	2.36	0.12
Rank	2	3	1	4

Table 7 — Response Table for Means for MRR

Level	Electrode	Discharge Current	Pulse ON Time	Pulse OFF Time
1	27.81	32.74	27.33	31.86
2	35.77	31.92	32.36	31.79
3		30.72	35.69	31.73
Delta	7.96	2.01	8.36	0.13
Rank	2	3	1	4

Table 8 — Response Table for Signal to Noise Ratios (Smaller is better):

Level	Electrode	Discharge Current	Pulse ON Time	Pulse OFF Time
1	-10.112	-6.727	-7.159	-8.561
2	-7.633	-8.643	-8.775	-8.788
3		-11.248	-10.684	-9.269
Delta	2.479	4.521	3.525	0.707
Rank	3	1	2	4

Table 9 — Response Table for Means of for SR

Level	Electrode	Discharge Current	Pulse ON Time	Pulse OFF Time
1	3.344	2.212	2.322	2.843
2	2.500	2.797	2.860	2.843
3		3.758	3.585	3.080
Delta	0.844	1.547	1.263	0.237
Rank	3	1	2	4

S/N Ratio and Means table for MRR in Table 6 and Table 7, respectively**.** Taguchi Analysis for SR depicts that the discharge current parameter has more significance followed by the Ton, Electrode wire material then T_{off} as shown in the Table of S/N Ratio and means a table of the SR in Table 7 and Table 8 respectively. The S/N response graph for MRR depicts that the brass is better electrode than copper due to higher tensile strength so can be operated at higher speeds that gives better MRR than copper. Also, with an increase in Ton, there is increased MRR due to high sparking time; Discharge Current has an inverse relationship with the MRR, and T_{off} is almost insignificant for MRR, as shown in Fig. 3.

3.1 Effect of variable parameters on MRR

The selection of electrode wire material carries a considerable role in the WEDM process due to its thermal and physical characteristics. Peak current allows a crater to develop after the open circuit voltage has been destroyed. The existence of this effect was only possible when the wire electrode of the cathode started emitting electrons, which clashed with the particles of dielectric fluid and increased the ionization process by generating more electrons and ions. S/N response graph Fig. 3 for MRR depicts that the brass is a better electrode than copper due to its higher tensile strength, so it can be operated at higher speeds that give better MRR than copper.

It was observed that the majority of MRRs were affected by current. Throughout the range (8A-12A), the MRR decreases marginally, while the MRR declines dramatically in the range (12A-16A). The decrease in MRR is due to contamination in the void of the plasma column. Such contamination is caused by particles from electrodes. As the current increases, the energy of the spark increases, which produces more debris. The debris created can bind to the workpiece material and cause unnecessary sparks, resulting in the degradation of the wire material, effects resulting in less MRR leading to a smaller amount of kerf width. MRR increases as T_{on} increases, but the rate of increase in value of MRR is more in the range of T_{on} (25μs -45μs) than the range of (45μs- 65μs). With further increase in T_{on} from 65μs -100μs, the rate of increase of MRR decreases slightly. It may be inferred from the reason with high T_{on}; large material melts at the interface of the tool and the workpiece, which requires desired flushing time, but as the value of T_{off} is too short relative to T_{on}, so no adequate time is there for flush out all the debris particles in between the machining zone, hence arcing will takes place which causes for decreasing MRR.

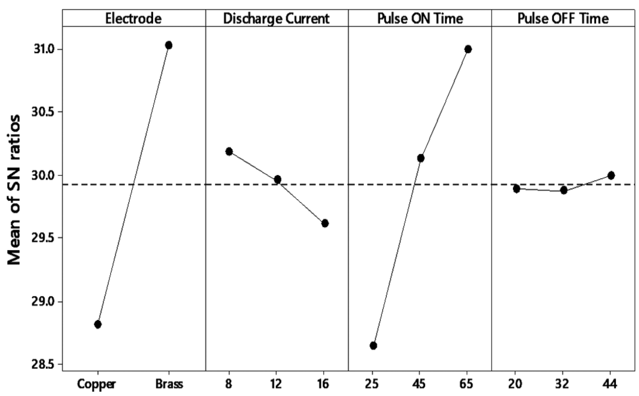

Fig. 3 — S/N response graph for MRR.

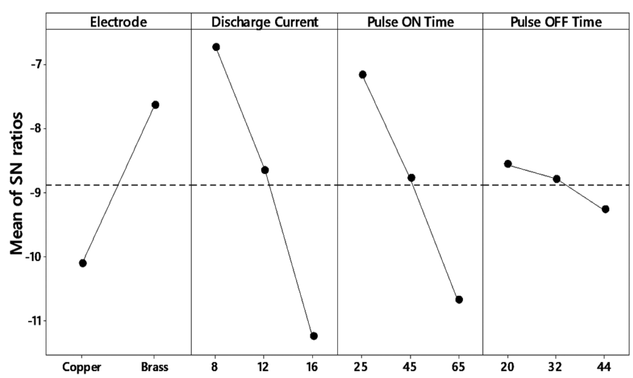

Fig. 4 — S/N response graph for SR.

3.2 Effect of variable parameters on SR

S/N response graph Fig. 4 for SR depicts that the brass is a better electrode than copper due to its higher tensile strength, so it can be operated at higher speeds that give a better surface finish than copper. Discharge current has been found to have a prominent effect on SR.

The graph indicates that SR increases with a rise in the current of discharge. The change in the discharge current results in higher energy from the spark, creating large and bigger pits on the surface. Increased SR is observed while increasing discharge current. Probably it can be that discharge energy becomes highly intense by rising machining current. So higher the discharge energy with deeper craters and greater melting, as well as evaporation, happened in the process gives a high SR. Due to the long T_{on} effect, some marks can be observed on the machined face leading to increased SR. When Ton increases from 25 μs to 65 μs, also there is an increase in SR, which indicates that total heat energy transmitted to the work surface in addition increased. During low Ton, the adhesion of debris to the surface is lowered, so the machined surface is free of any marks that ensure smooth machining with the superior surface profile. From ANOVA analysis, electrode material shows a maximum influence on MRR with a contribution of 55.74 % and next Pulse ON time with the contribution of 41.53 % and discharge current shows 2.39 % contribution with Pulse OFF time almost insignificant can be clearly observed from Table 10. From ANOVA analysis, discharge current shows the maximum influence on SR with the contribution of 43.18 % and next Pulse ON time with the contribution of 28.45 % and Electrode material shows 18.93 % contribution with Pulse OFF time almost insignificant that is 1.32 % on SR that can be clearly observed from Table 10. Figure. 5 shows the specimen before and after machining.

Table 10 — ANOVA Table for MRR and SR

Source	MMR			SR		
	F-Value	P-Value	% Contribution	F-Value	P-Value	%Contribution
Electrode	1752.43	0.000	55.74 %	23.39	0.001	18.93 %
Discharge Current	37.72	0.000	2.39 %	26.67	0.000	43.18 %
Pulse ON Time	652.86	0.000	41.53 %	17.57	0.001	28.45 %
Pulse OFF Time	0.15	0.866	0.009 %	0.82	0.469	1.32 %
Error			0.318 %			8.09 %
Total			100 %			100 %

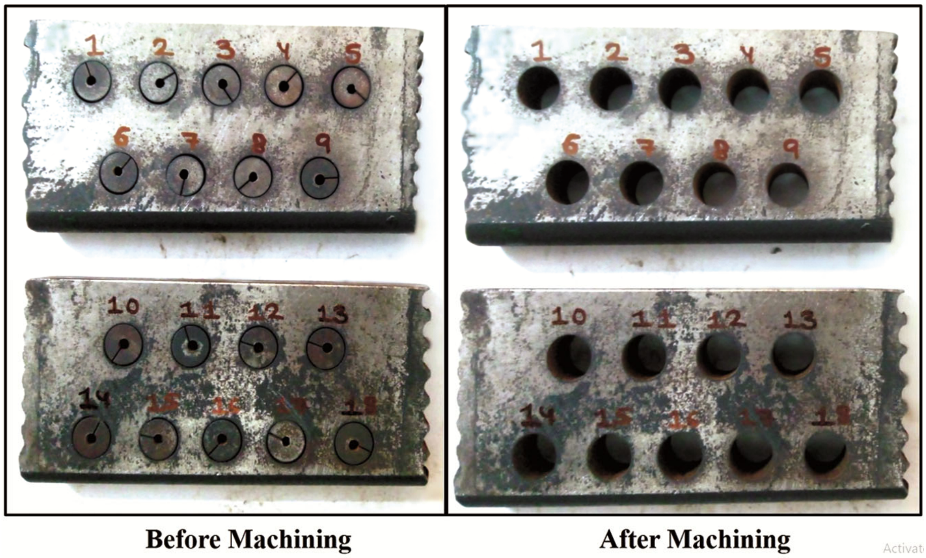

Fig. 5 — Specimen after CNC wire cut EDM.

4 Conclusion

In the current research, an effort was made to examine the consequence of parameters involved in the process such as Pulse ON Time, Pulse OFF Time, and Electrode Material (Copper and Brass), Discharge Current output variables such as MRR, SR for wire EDM. Initial tests are performed via an array of process parameters to design the process window. An Orthogonal Array was developed to perform 18 experiments, and corresponding output / associated responses such as SR and MRR were calculated or recorded. An additional surface meter was used to measure the Ra values of all the specimens after the wire-cut EDM machine. Optimization techniques such as Taguchi and ANOVA have been used to recognize optimum process parameters for the EDM process. The result of each and every control parameter on output performance measures it thoroughly and studied alone using the plot of the S/N ratio.

- It has been seen that Electrode Material and T_{on} were the most important factor affecting MRR.
- Based upon results obtained from ANOVA analysis, it has been observed that Discharge Current and T_{on} are the utmost significant parameters for SR.
- **Copper Wire:** Its easy availability with higher conductivity makes it a rational choice for the EDM wire electrode at the point, but as low tensile strength quickly made clear its limitations. So low Cutting Speed and Low MRR.
- **Brass Wire:** The zinc factor is applied to copper for manufacturing EDM brass wire; it is one of the most commonly used EDM wire used today. As zinc has lower melting /vaporization levels, that makes it a stronger electrode wire compared with copper, and the more zinc at the surface of the wire, the faster it would cut and the higher the MRR.
- Loss of heat and time required for debris particles to be separated from the machined region happens with increased pulse time off is good for better surface roughness.

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