A Review on the Usage of Different Optimization Techniques for Wire Electro Discharge Machining of Stainless Steels

Shatarupa Biswas[1*], Manidipto Mukherjee.[2]

[1]*Research Scholar, Department of Mechanical Engineering, NIT, Silchar- 788010, Assam, INDIA*

[2]*Sr. Scientist, CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, West Bengal, INDIA*

**Corresponding author's E-mail : supriticu@gmail.com,*

ABSTRACT

Wire electrical discharge machining (WEDM) is a non-traditional metal cutting procedure and the overall cutting process is contactless between the wire and work material. A plasma channel is created by the electrical energy between work piece and wire, which convert the electrical energy into thermal energy and the temperature rises (8000°C to 12000°C). Due to this mechanism, metal is melted from the upper surface of work piece. Generally difficult to machine material is used to cut in WEDM. However, stainless steel (SS) is one of them, it is a metal alloy, which is mixed with steel and other elements such as chromium (Cr), nickel (Ni), molybdenum (Mo), silicon (Si), carbon (C), nitrogen (N_2), and manganese (Mn) etc. SS has some excellent properties, such as high durability, high tensile strength, and corrosion resistant etc. Due to these properties SS is mainly used in automobile industries, biogas tank, combustion chamber and petrochemical industries etc. The present paper discussed about the machining of different SS grades in WEDM and effect of several input parameters (such as pulse on time (T_{on}), pulse off time (T_{off}), servo voltage (SV), wire feed (WF) etc.) on response parameters (such as material removal rate (MRR), surface roughness (SR), kerf width (KW) etc.). The review paper also reports the uses of different optimization techniques (such as taguchi technique (TT), response surface method (RSM), gray relational analysis (GRA) etc.) on various SS grades for optimizing the response parameters on the basis of different input variables. Furthermore, the research shows how to vary the value of output responses corresponding to input parameters value.

***Keywords*:** WEDM; stainless steels; input variables; output variables; optimization techniques.

1. INTRODUCTION

Stainless steel (SS) is erosion resistant at high temperatures, and provided high strength, therefore, manufacturers started to use SS in industries (bulk materials handling apparatus, building outsides and roofing equipment, automobile devices, chemical processing plants, petroleum refineries, shipbuilding and marine industry, pollution control equipment, and transportation machinery). SS is made of some primary components which is generally found in the earth's crust (iron ore, chromium, silicon, nickel, carbon, nitrogen, and manganese etc.). Normally, SS can be classified into five categories according to their metallurgical structure, these are (i) Austenitic SS (304, 316 etc.), (ii) Martensitic SS (410, 420 etc.), (iii) Ferritic SS (409L, 410L etc.), (iv) Duplex SS (X2CrNiN22-2, X2CrNiN23-4 etc.) and (v) Precipitation hardening SS (17-4 PH, 17-7 PH etc.). During traditional machining (such as Lathe, drilling etc.), SS undergoes some difficulties like formation of long chip which gives rise to built up edge (BUE) on rack faces, and it increased the cutting tool wear rate and reduced the quality of surface integrity of work piece to a great extent. However, to overcome these difficulties non-conventional (EDM, WEDM, ECM etc.) machining is adopted. WEDM is one of them, it is basically used to cut difficult shapes [1]. In WEDM, wire is connected to the -ve terminal which is known as the cathode; however, the workpiece is connected to the +ve terminal which is known as the anode. Furthermore, deionized water is used as a dielectric fluid, its cooling rate and low viscosity [1, 2]. During the cutting operation ions combine together and sparks are created [3]. For this reason, WEDM is also known as the spark erosion machining process. The gap (0.025mm-0.05mm) is required between wire and work piece [4] to generate the spark and then temperature increased (8000°C-12000°C) [5]. The wire is made by zinc or brass or molybdenum etc. and the wire diameter's is vary 0.05mm - 0.30 mm [6-8]. In WEDM, up to 300 mm thick work piece can be machined with close tolerance of ±0.0001mm [1]. Figure 1. shows the basic working principle of WEDM process. The major limitation of this process is, only conductive materials (such as copper, gold, silver, etc.) are applicable for machining [9].

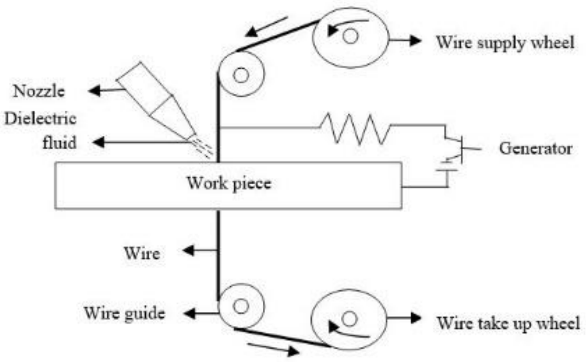


Figure 1. Working principle of WEDM

However, lots of studies have been done on WEDM process with different materials, but limited research reported about the machining of various SS grades. The goal of the current study is to show an overall view of SS grades machining using WEDM and to improve the outcomes i.e., material removal rate (MRR), surface roughness (SR), kerf width (KW) etc. on input parameters i.e., current (C), servo voltage (SV), pulse on time (T_{on}), pulse off time (T_{off}) etc. using different optimization techniques (OT). Because, selection of input parameters value which can improve output parameters value would be very difficult without a proper OT. Many researchers have been used several OT's, such as grey relational analysis (GRA), artificial neural network (ANN), taguchi technique (TT), response surface method (RSM), and fuzzy theory (FT) etc. to improve the response parameters. This paper is a review paper on several grades of SS machining by WEDM and it shows the parametric optimization of different SS grades using different types OT's.

2. VARIOUS GRADES OF SS

SS shares some unique characteristics (such as high tensile strength, very durable, recyclable, long lasting etc.). Due to its versatility, durability and affordability SS production continue to increase around the world year after year. However, SS is not a single alloy, it combines with various metals alloys such as Cr (minimum 11%), Ni and Mo. Generally, SS can be classified into five categories according to their metallurgical structure. Figure 2. shows the classification of SS and their uses.

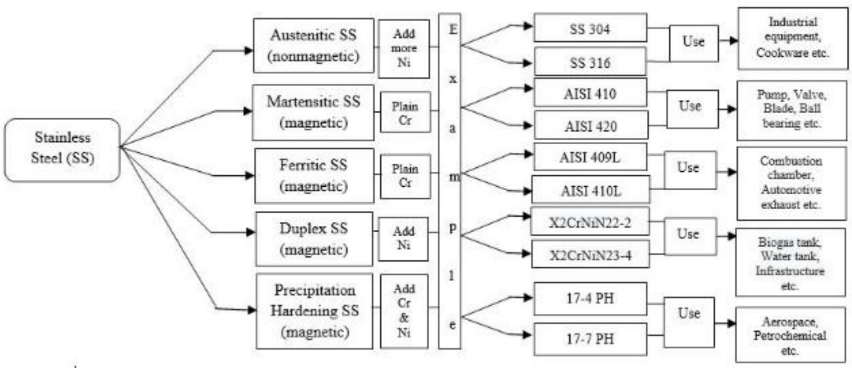


Figure 2. Classification of SS and their uses

2.1. Austenitic SS

Austenitic is a nonmagnetic [10] and when more Ni percentage is added then SS metallurgical structure changes (body centered cubic (BCC) to face centered cubic (FCC)). Austenitic SS is used for making of industrial equipment's, surgical equipment's, nuclear vessels etc.[11]. The steel is formable, weldable, has high corrosion resistance and oxidation resistance. It can be used (-150°C to -273°C) to (<460°C), Austenitic SS is extensively used among other SS grades and mostly used austenitic 200 series (201, 202, 205 etc.) and 300 series (301, 302, 303, 304, 304L, 316, 316L etc.) in industries [12]. Apart from this SS 316L is widely used in modern industry which has extra corrosion resistance due to its high % of Cr and Ni and low C% [13]. Some Austenitic SS grades are tabulated in Table 1.

Table 1. Grades, chemical compositions, and mechanical properties of Austenitic SS.

AISI number	UNS number	EN number	Chemical composition (% in weight)	Mechanical properties	Physical properties
301	S30100	1.4310	Cr=16.00-18.00, Ni=6.00-8.00, Mn=2.00, C=0.15, S=0.03, P=0.045, Si=1.00.	σ_t=758 MPa, γ=276 MPa, µ=0.27-0.28, HRB=86.	ρ=7.88 g/cm^3, E=193 GPa, M_{temp}=1399°C-1421°C.
302	S30200	1.4310	Cr=17.00-19.00, Ni=8.00-10.00, Mn=2.00, C=0.15, S=0.03, P=0.045, Si=1.00.	σ_t=620 MPa, γ=275 MPa, µ=0.27-0.3, HRB=85.	ρ=7.90 g/cm^3, E=19 GPa M_{temp}=1399°C-1421°C.
303	S30300	1.4305	Cr=17.00-19.00, Ni=8.00-10.00, Mn=2.00, C=0.10, S=0.35, Si=1.00.	σ_t=690 MPa, γ=415 MPa, µ=0.25, HRB=96.	ρ=7.80 g/cm^3, E=193 GPa, M_{temp}=1400°C-1420°C.
304	S30400	1.4301	Cr=18.00, Ni=8.00, Mn=2.00, N=0.10, C=0.08, S=0.03, Si=0.75, P=0.045.	σ_t=515 MPa, γ=205 MPa, µ=0.29, HRB=92.	ρ=8.00 g/cm^3, E=195 GPa, M_{temp}=1399°C-1454°C.
304L	S30403	1.4307	Cr=18.00, Ni=8.00, Mn=2.00, N=0.10, C=0.03, S=0.03, Si=0.75, P=0.045.	σ_t=485 MPa, γ=170 MPa, µ=0.28, HRB=92.	ρ=8.03 g/cm^3, E=195 GPa, M_{temp}=1400°C-1450°C.
316	S31600	1.4401	Cr=16.00-18.50, Ni=0.00-14.00, Mn=2.00, Mo=2.00-	σ_t=515 MPa, γ=205 MPa, µ=0.27-0.28,	ρ=7.99 g/cm^3, E=193 GPa, M_{temp}=1371°C-

			3.00, Si=1.00, N=0.10, C=0.08, P=0.05, S=0.03.	HRB=95.	1399°C.
316L	S31603	1.4404	Cr=16.00-19.00, Ni=10.00-15.00, Mn=2.00, Mo=2.00-3.00, Si=1.00, C=0.03, S=0.03, P=0.05.	σ_t=485 MPa, γ=170 MPa, μ=0.27-0.3, HRB=95.	ρ=7.99 g/cm^3, E=193 GPa, M_{temp}=1390°C-1440°C.

2.2. Martensitic SS

Martensitic SS is a hard form of crystalline structure. There is a distinct similarity of its crystalline structure with Ferritic steel grades body center tetragonal (BCT) crystal lattice. This steel has some properties (such as high hardness, high strength etc.) [14]. Among the martensitic SS, AISI 410, AISI 420, AISI 431 etc. are the most common grades. Martensitic SS is basically used for producing pump, valve, blade, ball bearing etc. and it can be classified into two categories according to their C%. First one is high carbon Martensitic SS (C% range is 0.61-1.50), another is low carbon Martensitic SS (C% range is 0.05-0.25). Some Martensitic SS are shown in Table 2.

Table 2. Grades, chemical compositions, and mechanical properties of Martensitic SS.

AISI number	**UNS number**	**EN number**	**Chemical composition (% wt.)**	**Mechanical properties**	**Physical properties**
410	S41000	1.4006	Cr=11.80, Ni=0.50, Mn=0.40, Si=0.30, C=0.14, P=0.04, S=0.01.	σ_t=290 MPa, γ=510 MPa, μ=0.28-0.29, HRB=81.	ρ=7.74 g/cm^3, E=200 GPa, M_{temp}=1480°C-1530°C.
420	S42000	1.4021	Cr=12.80, Ni=0.50, Mn=0.40, Si=0.40, C=0.38, P=0.04, S=0.01.	σ_t=700-950 MPa, γ=500 MPa, μ=0.28, HRB=87.	ρ=7.73 g/cm^3, E=200 GPa, M_{temp}=1454°C-1510°C.
431	S43100	1.4057	Cr=15.00-17.00, Ni=1.25-2.50, Mn=1, Si=1.00, C=0.20, P=0.04, S=0.03.	σ_t=800-950 MPa, γ=600 MPa, μ=0.28-0.29, BHN=295.	ρ=7.80 g/cm^3, E=200 GPa, M_{temp}=1482°C .

440C	S44004	1.4125	Cr=17.00, Mn=1.00, Si=1.00, C=1.10, Mo=0.75.	σ_t=760-1970 MPa, γ=450-1900 MPa, μ=0.27-0.30, HRB=97.	ρ=7.80 g/cm^3, E=200 GPa, M_{temp}=1483°C.

2.3. Ferritic SS

Ferritic SS contains higher Cr (10-30%) than Martensitic SS. It has excellent corrosion resistance, elevated temperature oxidation resistance, and higher strength etc. In metallurgical structure this steel has body centered cubic (bcc) crystal structure. Among the Ferritic grades AISI 409L, AISI 430, AISI 439 grades are basically used for manufacturing valve, combustion chamber, automotive exhaust etc. Some common grades of Ferritic SS are shown in Table 3.

Table 3. Grades, chemical compositions, and mechanical properties of Ferritic SS.

AISI number	UNS number	EN number	Chemical composition (% wt.)	Mechanical properties	Physical properties
409	S40900	1.4512	Cr=10.50-11.70, Ni=0.50, Mn=1.00, Si=1.00, C=0.03, P=0.04, S=0.02, N=0.03, Ti=0.15-0.50.	σ_t=360 MPa, γ=175 MPa, μ=0.28, HRB=88.	ρ=7.75 g/cm^3, E=200 GPa, M_{temp}=1425°C-1510°C.
409L	S409L00	1.4512	Cr=10.50-11.70, Ni=0.50, Mn=1.00, Si=1.00, C=0.03, P=0.04, S=0.02, N=0.03, Ti=0.50, Nb=0.17.	σ_t=380 MPa, γ=170 MPa, μ=0.28-0.29, HRB=88.	ρ=7.80 g/cm^3, E=200 GPa, M_{temp}=1454°C.
430	S43000	1.4016	Cr=16.00-18.00, Ni=0.75, Mn=1.00, Si=1.00, C=0.12, P=0.04, S=0.03.	σ_t=450 MPa, γ=205 MPa, μ=0.28-0.29, HRB=89.	ρ=7.74 g/cm^3, E=200 GPa, M_{temp}=1425°C-1510°C.

410S	S41008	1.4000	Cr=11.50-13.50, Ni=0.60, Mn=1.00, Si=1.00, C=0.08, P=0.04, S=0.03.	σ_t=415 MPa, γ=205 MPa, µ=0.27-0.30, HRB=89.	ρ=7.76 g/cm^3, E=200 GPa, M_{temp}=1482°C-1532°C.
439	S43932	1.4510	Cr=17.00-19.00, Ni=0.50, Mn=1.00, Si=1.00, C=0.03, P=0.04, S=0.03, N=0.03, Al=0.15, Ti+Nb=0.75.	σ_t=415 MPa, γ=205 MPa, µ=0.27-0.29, HRB=89.	ρ=7.70 g/cm^3, E=193 GPa, M_{temp}=1505°C.

2.4. Duplex SS

Duplex SS steel is a combination of γ Austenite (fcc lattice) and α Ferrite (bcc lattice) in phases. It has high strength, low thermal conductivity, and good corrosion resistance (because of high% Mo) [15]. Duplex SS is mainly used for making infrastructure, pressure vessels, water and biogas tank etc. This steel can be classified into four categories i.e., Lean Duplex SS (2101, 2102, 2404), Duplex SS (2205, 2304, 2003), Super Duplex SS (2507, Z100, 255) and Hyper Duplex SS (2707) [16]. The Duplex SS is not as expensive as other popular SS grades, because it has less quantity of Ni, moreover, equivalent quantity of Ferrite SS and Austenite SS. Few Duplex SS are shown in Table 4.

Table 4. Names, chemical compositions, and mechanical properties of Duplex SS.

Duplex SS	UNS number	EN number	Chemical composition (% wt.)	Mechanical properties	Physical properties
DX 2202	S32202	1.4062	Cr=21.50-24.00, Ni=1.00-2.90, Mn=2.00, Si=1.00, C=0.03, P=0.04, S=0.01, N=0.16-0.28, Mo=0.45.	σ_t=770–800 MPa, γ=530 MPa-630 MPa, µ=0.27, BHN=290.	ρ=7.70 g/cm^3, E=200 GPa, M_{temp}=1380°C-1430°C.
2507	S32750	1.4410	Cr=24.00-26.00, Ni=6.00-8.00, Mn=2.00, Si=1.00, C=0.03, P=0.04,	σ_t=850 MPa, γ=600 MPa, µ=0.27, BHN=260.	ρ=7.81 g/cm^3, E=200 GPa, M_{temp}=1400°C-1450°C.

			S=0.01, N=0.24-0.35, Mo=3.00-4.50.		
2304	S32304	1.4362	Cr=22.00-24.50, Ni=3.50-5.50, Mn=2.00, Si=1.00, C=0.03, P=0.04, S=0.01, N=0.50-2.00, Mo=0.10-0.60.	σ_t=600-830 MPa, γ=400 MPa, μ=0.27, BHN=230.	ρ=7.70 g/cm^3, E=200 GPa, M_{temp}=1380°C-1420°C.
2205 UR45N	S32205	1.4462	Cr=21.00-23.00, Ni=4.50-6.50, Mn=2.00, Si=1.00, C=0.03, P=0.04, S=0.02, N=0.10-0.22, Mo=2.50-3.50.	σ_t=780 MPa, γ=520 MPa, μ=0.27, BHN=240.	ρ=7.80 g/cm^3, E=200 GPa, M_{temp}=1400°C-1450°C.

2.5. Precipitation Hardening (PH) SS

Precipitation hardening SS contains of Ni and Cr [17]. However, this SS grade is a mixture of Martensitic and Austenitic properties. After machining the grade, low temperature heat treatment can be applied to elevate its strength. For its strength criteria Precipitation hardening SS finds its extensive use in aerospace industries. Based on its microstructure (pre heat treatment), SS (PH) can be classified into three categories, i.e., Martensitic (17-4 PH,), semi-Austenitic (17-7 PH), and Austenitic (A-286). Some PH SS grades are shown in Table 5.

Table 5. Grades, chemical compositions, and mechanical properties of Precipitation hardening (PH) SS.

AISI number	UNS number	EN number	Chemical composition (% wt.)	Mechanical properties	Physical properties
630	S17400	1.4542	Cr=15.00-17.00, Ni=3.00-5.00, Mn=1.50, Si=0.70, C=0.07, P=0.04, S=0.02, Mo=0.60.	σ_t=880–1470 MPa, γ=580 Mpa-1300 MPa, μ=0.28, BHN=260.	ρ=7.80 g/cm^3, E=200 GPa, M_{temp}=1380°C-1430°C.
631	S17700	1.4568	Cr=16.00-18.00, Ni=6.50-7.75, Mn=1.00, Si=1.00, C=0.09, P=0.04, S=0.03, Al=0.75-1.50.	σ_t=1180-1650 MPa, γ=430 MPa-650 MPa, μ=0.28, BHN=180–430 HB.	ρ=7.70 g/cm^3, E=200 GPa, M_{temp}=1400°C-1440°C.

3. IMPORTANT PARAMETERS IN WEDM

In WEDM, machining of material is entirely dependent over the use of various input parameters. The output parameters are dependent over these input parameters. Deferent types of input parameters and output parameters are shown in Figure 3.

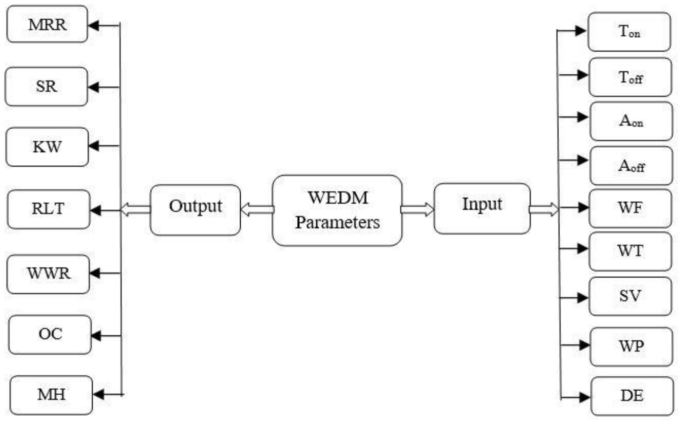


Figure 3. Parameters of WEDM

3.1. Input parameters

The main input parameters are shown in below.

- **Pulse on time (T_{on}):** When current is applied between the work piece and the wire, then spark is occurred and material is melted, this sparking time duration is called T_{on} and measurement unit is microsecond (μs).
- **Pulse off time (T_{off}):** When no current is applied between the wire and the work piece is called T_{off}. The measuring unit of T_{off} is microsecond (μs).
- **Arc on time (A_{on}):** When voltage is applied between work piece and wire then sparking is going on, this time is called A_{on}. It's measuring unit is microsecond (μs).
- **Arc off time (A_{off}):** When no spark i.e., no discharge is occured between work piece and wire is called A_{off}. The measuring unit of A_{on} is microsecond (μs).
- **Wire feed (WF):** A unit of wire length passing through a point per unit time is called WF and measuring unit of WF is millimeter/minute.
- **Wire tension (WT):** The tensile force of wire in between the upper nozzle and the lower nozzle is named as WT and measuring unit of WT is gram (gm) or Newton (N).
- **Servo voltage (SV):** The working voltage is SV and its measuring unit is volt (v).
- **Water pressure (WP):** An amount of perpendicular force applied on an object per unit area, is called as WP and it's measuring unit is Pascal (Pa).
- **Discharge energy (DE):** For spark when the material is removed then electrical energy is available between tool and the specimen. It depends on the level of discharge energy/pulse. It can be measured with the help of the following equation (1)[18] and it's measuring unit is Joule (J).

$$DE = \int_0^{t_d} \mathrm{v} \times \mathrm{i} \times \mathrm{dt} \cong \mathrm{v} \times \mathrm{i} \times \mathrm{t}_d \qquad (1)$$

Where, t_d= discharge time, i = discharge current, v = discharge voltage.

3.2 Output parameters

The output parameters are shown in below.

- **Material removal rate (MRR):** It can be expressed as the amount of material eroded per unit time. However, it offers the rate of cutting is quick or slow, which is very vital to regulate the mass production. Measuring unit of MRR is millimeter^3/minute. When SV is higher, MRR is lower and when T_{on} is higher then, MRR is also higher. MRR is calculated by the following equation (2) [19, 20].

$$MRR = cutting\ velocity \times\ kerf\ width\ \times thickness\ of\ job \qquad (2)$$

- **Surface roughness (SR):** SR is calculated by the deflection of the normal vector to a real surface of work piece. If the measured deflection is higher, then the surface quality is rough, if the measured deflection is lower, then the surface quality is smooth. The measuring unit of SR is micrometer (µm) and it can be measured by the surface roughness tester apparatus [21].

- **Kerf width (KW):** After the machining operation of material, the cutting width is called KW and it controls the dimensional accuracy of the machining product [22]. The measurement of KW is done by optical microscope and measuring unit is micrometer (µm) [20]. KW is calculated by the equation (3) [23].

$$KW = wire\ diameter + (2 \times Spark\ gap) \quad (3)$$

- **Recast layer thickness (RLT):** RLT is formed in the work piece's top surface [24], when the machining is going on then the spark creates between wire and job, as a result in a sudden rise in localized heat which melts the cutting surfaces to an extent followed by rapid quenching due to the presence of dielectric fluid. This phenomenon produces a surface layer that resembles the cast state, and is known as an RLT. It's measurement unit is micrometer (µm) and it can be measured by scanning electron microscopy (SEM) [24].

- **Wear wire rate (WWR):** It is the ration of wire weight loss (WWL) and wire initial weight (IWW), calculated by the following equation (4) [25].

$$WWR = WWL/IWW \quad (4)$$

- **Over cut (OC):** After the cutting, the width of cutting is slightly higher than the wire diameter because of spark diameter variation. OC can be measured and it's measuring unit is millimetre (mm). The following equation (5) [26] is help to calculate the OC.

$$OC = \frac{KW - wire\ diameter}{2} \quad (5)$$

- **Micro hardness (MH):** Hardness is a property of material; it defines the resistance under a static load of metal. After cutting, the material's MH is measured by the micro hardness tester machine with the dwell time and a minor load. Basically the test is done by Vickers Hardness tester [27]. It's measuring unit is HV and hardness is calculated by the following equation (6) [28].

$$HV = \frac{2\,F\,\sin\left(\frac{136^{\circ}}{2}\right)}{d \times d} \quad (6)$$

Where, F is the applied load and *d* is the diagonals (two) mean of a squared pyramid which has an angle of 136°.

However, the present review paper is mainly focused on machining of different SS grade in WEDM. Therefore, required useful input parameters which can be improved output parameters value. Furthermore, for finding the optimum value of output parameter, suitable selection of OT is most important. Various types of OT's are elaborated below.

4. OPTIMIZATION TECHNIQUE (OT)

Presently the manufacturing industries focus on assembling a good quality product with minimum price and lesser time. Therefore, to fulfill the requirements used various types of OT's [29] is needed. Thus, the choice of appropriate machining parameter is critical to achieve the best outcomes. Figure 4. shows the numerous types of OT's.

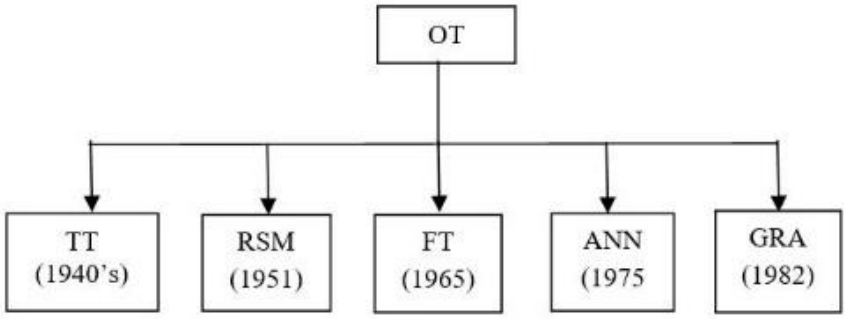


Figure 4. Numerous types of OT

4.1. Taguchi technique (TT)

Taguchi technique (TT) is robust a design method and it developed by Dr. Genichi Taguchi in1940's [30]. The technique develops the quality of existing products and processes and at the same time decreases their costs [31]. TT accomplishes this by creating the process performance to differentiate factors such as metals, manufacturing apparatus, and conditions related to its operations. TT mentions a three stage process such as the design of the system, design of parameter and design of tolerance [31]. This method is used for estimating and improvement of products, which improved the based on significant variables and controlled the process, and also improved the procedure to yield the optimum values. Furthermore, TT mentions an orthogonal array (OA) for lying out of testing. Therefore, Design of experiment (DOE) is used to select the most appropriate OA. After that analysis of variance (ANOVA) is used for determining the percentage influence of each process parameter against the response parameter. Furthermore, TT is used as a statistical measure of performance which is called signal to noise ratio (S/N). The S/N ratio can be used to measure the deviation of the response parameters from the input variables. There are three classifications of S/N ratio's shown in the following equation numbers 7-9 [31].

1. Larger is the better-

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \quad (7)$$

2. Smaller is the better-

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (8)$$

3. Nominal is the better-

$$\frac{S}{N} = -10\log\left(\frac{y}{S_{y^2}}\right) \quad (9)$$

Where Y_i = tentatively watched worth, n = repeated number of each examination, y = normal of watched information, and S_y^2 =difference of Y_i for each kind of attributes.

4.2. Response surface method (RSM)

RSM is introduced by E.P. Box and K.B. Wilson in 1951 [31]. The 1st and 2nd order polynomial models are used to estimate the problems, these are shown below [40]. However, RSM is mainly used for making a model and to generate a relation between input parameter and output parameter [31]. For this reason, required two equation which is shown below.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \xi \quad (10)$$

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i,j=1\ i=j}^{k} \beta_{ij} x_i x_j + \xi \quad (11)$$

Where Y = mistake, x_i = linear input factors, x_i^2 and $x_i x_j$ are the squares and association term. The 2nd order unknown coefficients are β_0, β_i, β_j and β_{ii}.

4.3. Fuzzy theory (FT)

FT is discovered by Lotfi Zadeh in 1965 [32], the technique is a mathematical modeling technique and it calculated by the membership functions. The correlation between process parameters and response parameters is described by a set of language statements. FT numbers are correlated with a number of fuzzy sets for every input variable. It has some conditional statements (If-Then rules) [35] and multiple statements are joined by "And" rule. The output of FT will be a single scalar quantity. Defuzzifying is the transformation of fuzzy quantity and fuzzifying is the transformation of a precise quantity which is useful in FT. The popular seven types defuzzifying methods are (a) centroid method, (b) average weight method, (c) mean of maxima, (d) membership method, (e) center of sums method, (f) center of largest area method, (g) first (or last) of maxima method [32]. Defuzzification technique selection is difficult and has an important influence on the speed and correctness of the fuzzy model. Generally centroid (for defuzzification) method is used because it offers more accurate results than others and appropriate for a multi-dimensional fuzzy problem.

4.4. Artificial neural network (ANN)

In the year of 1975 Paul J.Wearbos's described the multi-layer networking process of back propagation algorithm enabled practical training [33]. ANN is a modeling tool which uses a software computing technique to solve non-linear complex problems. Also ANN has abilities of learning to map between the input variables and the performance parameters [32]. The technique is similar to the human brain's neuron system and it collects data by a learning process [34]. An ANN can solve the tough problems whose analytical or numerical solutions are difficult. Usually, ANN's design has three layers, first one is how layers are organized and how they are connected to each other. Second one is how data is stored, next is how the ANN produces responses for input variables. The procedure of ANN includes the input data of the network, the hidden layer's number with neurons and an output layer. Generally, ANN can be classified into two categories. One is feed forward (FF) and another is back propagation networks (BPN). FF networks flow in a sequence from the input nodes to the output nodes. In a BPN, signals may spread from any output neuron to any input neuron. The network diagram of ANN is appeared in figure 5.

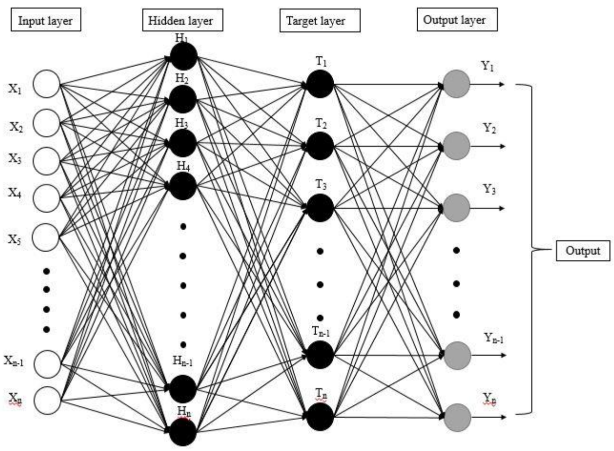


Figure 5. Bubble diagram of ANN technique

4.5. Gray relational analysis (GRA)

GRA is invented by Julong Deng in 1982 [31]. The technique is used to solve the complex inner relationships among the various performance parameters [32] and multi objective optimization problems [35]. The system does not need adequate evidence to compute the behavior of an uncertainty system with distinct data problems. GRA technique includes with three colors, first one is black i.e. when no information is available. The second one is white i.e. when all information's are available and last one is grey system i.e. when information's are imperfect. The main advantage of GRA is, its calculation steps are easy. For this, GRA is used in the engineering and management region. The calculating steps of GRA has three conditions:

First step: Three main conditions are listed below with equation number (12 - 14) [31].

1. Lower is the better

$$x_i^*(k) = \frac{x_i(k) - min\, x_i(k)}{max\, x_i(k) - min\, x_i(k)} \quad (12)$$

2. Higher is the better

$$x_i^*(k) = \frac{max\, x_i(k) - x_i(k)}{max\, x_i(k) - min\, x_i(k)} \quad (13)$$

3. Nominal is the best

$$x_i^*(k) = \frac{1 - |x_i(k) - x_o\, b(k)|}{max\, x_i(k) - x_o\, b(k)} \quad (14)$$

Where i= 1….m, k = 1…m, $x_i(k)$ is the standardized approximation of the k^{th} component in the i^{th} arrangement, $x_0b(k)$ =estimation of the k^{th} quality element, max $x_i(k)$ =biggest estimation of $x_i(k)$, and min $x_i(k)$ =littlest estimation of $x_i(k)$.

Second step: Deviation calculation is listed below with equation number (15) [35].

$$\Delta_{oi}(k) = ||\, x_0^*(k) - x_i^*(k)\, || \quad (15)$$

Where, $x_o^*(k)$=1 maximum normalized value

Third step: Gray Relational Coefficient (GRC) calculating equation (16) [35, 36] is shown below.

$$\zeta_i(k) = \frac{\Delta_{min} + \zeta\, \Delta_{max}}{\Delta_{oi}(k) + \zeta\, \Delta max} \quad (16)$$

Where, k is the GRC for k^{th} performance in i^{th} experiment.

Δ_{min}= min $||\, x_0^*(k)-x_i^*(k)\, ||$ and Δ_{max}= max $||\, x_0^*(k)-x_i^*(k)\, ||$

ζ = coefficient of the technique, its value is generally 0.5

Last step: Grey Relational Grade (GRD) calculating equation (17) [35] is shown below.

$$\gamma_i = \sum w_i(k) \times \zeta_i(k) \quad (17)$$

Where, γ_i is GRD and w_i (k) is responses parameters weight.

Lots of researches have been carried out on SS (different grades) machining by WEDM using different OT to optimize the responses. Figure 6 shows researched year vs number of previous research papers on SS (different grades) machining in WEDM and Figure 7 shows the percentage uses of different SS grades in earlier research.

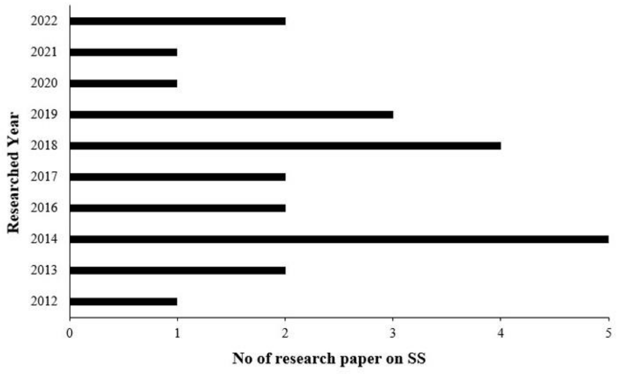


Figure 6. Researched year vs Number of researched paper.

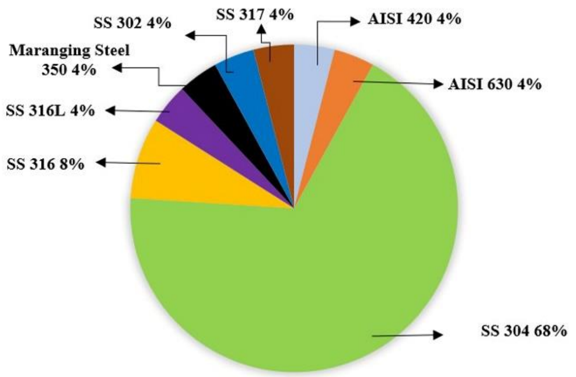


Figure 7. Uses of different SS grades

5. EARLIER RESEARCHES SUMMERY

Table 6. Earlier researches on machining of SS (various grades) by WEDM.

Year	Author	Material	Wire	Input Parameters	Output Parameters	OT	Finding
2012	Lingadurai et.al.[11]	SS 304	Brass	T_{on}, T_{off}, WF, GV	MRR, SR, KW	L18 Array, ANOVA	It is observed GV is the most effective process parameter for finding maximum MRR (0.0511 g/min). For finding minimum SR (1.5 µm) and minimum KW (0.333 mm), WF and T_{on} are the important parameters.

2013	Durairaj et. al.[37]	SS 304	Brass	GV, T_{on}, T_{off}, WF	SR, KW	TT, GRA	It is found that minimum SR and KW values are 2.02 µm and 0.289 mm respectively when TT is used and when GRA is used the above-mentioned values are 0.7088 µm and 0.9175 mm.
2013	Geetha et. al.[38]	SS 304	Brass	T_{on}, T_{off}, WT, WP	SR	RSM	It is discovered SR shows minimum=1.42 µm for T_{on} =114 µs, T_{off}=60 µs, WT=7 Gm, and WP=8 Kg/cm^2.
2014	Khan et. al.[39]	SS 304		T_{on}, T_{off}, C	KW, SR	TT, L9 Array, GRA	It is observed SR=2.88 µm for T_{on}=15 µs, T_{off} =3 µs, and C=2 amp and KW=0.210 mm for T_{on} =15 µs, T_{off}=5 µs, and C=3 amp when TT is applied. But when T_{on}=25 µs, T_{off} =3 µs, and C=4 amp shows minimum SR and KW values (2.371 µm), (0.333 mm) when GRA is used.
2014	Paliwal et. el.[40]	SS 302	Molybdenum	T_{on}, T_{off}, C	KW, SR	TT, L9 Array	It is found that KW =0.236 mm for C =3 amp, T_{on} =15 µs, T_{off} =4 µs respectively and SR=3.25 µm for C=3 amp, T_{on}=20 µs, T_{off} =5

							μs.
2014	Raju et.al.[41]	SS 316 L	Brass	T_{on}, C, SV, WT	SR	L16 Array, ANOVA	It is observed SR=1.54 μm for T_{on} =15 μs, C =9 amp, SV =5 v, and WT=12 m/min and it is found T_{on} is most significant factor.
2014	Nayak and Mahapatra [42]	SS 304	Broncocut-W	PT, TA, T_{on}, C, WF, WT	AE, SR, CS	TT, L27 Array, ANOVA	It is shown that taper cutting is a difficult operation for cutting deep slots with multiple angles. SR=2.15 μm for T_{on} =14 μs, C= 32 amp, WF=120 mm/s, and WT=16 N. CS shows maximum for T_{on}=18 μs, C=24 amp, WF=150 mm/s, and WT=16 N.
2014	Mathew et al.[43]	SS 304	Brass	T_{on}, T_{off}, WF, GV, WT, WP	MRR, SR	TT, L27 Array	It is observed that T_{on} is a most significant parameter for finding maximum MRR (15.423 mm^3/min) and minimum SR (1.71 μm).
2016	Kumar et.al.[44]	SS 304	Brass, Diffused wire	T_{on}, T_{off}, SV	MRR	TT, L9 Array	It is discovered that MRR shows maximum value, when used diffused wire=11.18 mm^3/min and brass wire=10.97 mm^3/min

							respectively. For both cases input parameters values are T_{on}=125 µs, T_{off}=45 µs, and SV=35 v.
2016	Bharathi et. el.[45]	SS 304	Brass	T_{on}, T_{off}, WF, SV	MRR, SR, KW	TT, L18 Array	It is found that SR=1.5 µm for SV=60 v, T_{on}=4 µs, T_{off}=4 µs, and WF=5 m/min. KW=0.333 mm for SV=50 v, T_{on}=4 µs, T_{off} =6 µs, and WF=5 m/min. Whereas MRR=0.0511 g/min for SV=50 v, T_{on}=6 µs, T_{off}=4 µs, and WF=7 m/min.
2017	Suresh et.al.[46]	SS 304	Brass, Zinc coated brass	T_{on}, T_{off}, WT, WF	MRR	L8 Array, ANOVA	It is found that MRR shows maximum (98.08 mm^3/min) for using Zn coated brass wire.
2017	Nayak and Mahapatra [47]	SS 304	Broncocut-W	PT, TA, T_{on}, C, WF, WT	AE, SR, CS	Fuzzy, BPNN, L27 Array	It is observed T_{on} and C are the most significant parameters for finding minimum SR=2.145 µm and maximum CS=1.66 mm/min.
2018	Babu and Subbaratnam[48]	SS 304	Molybdenum	T_{on}, T_{off}, C, WF	MRR	TT, L9 Array	It is invented MRR=25.23 mm^3/min for T_{on}=35 µs, T_{off} =10 µs, C=3 amp, and WF=2 m/min.

2018	Ugrasen et.al.[49]	SS 304	Molybdenum	T_{on}, T_{off}, C, BS	MRR, SR	TT, L27 Array	It is observed that T_{on} is the significant input variable for finding minimum SR (1.76 µm) and maximum MRR (17.15 mm^2/min).
2018	Choudhuri et.al. [50]	SS 304	Brass	T_{on}, T_{off}, C, SV, WT	SR, RLT	L13 Array, ANOVA, ANN	It is discovered that SR=1.851 µm for T_{on}=0.35 µs, T_{off}=15 µs, C=160 amp, V=30 v and WT=0.6 kg. On the other hand, RLT=5.26 µm for T_{on}=0.35 µs, T_{off}=30 µs, C=220 amp, V=60 v, and WT=1.2 kg.
2018	Padmavathi et al.[51]	SS 316	-	T_{on}, T_{off}, WF, WT, C	MRR, SR	TT, L27 Array	It is observed that C and T_{on} are the most effective process parameters for finding maximum MRR (25.5 mm^2/min) and minimum SR (3.20 µm).
2019	Ishfaq et.al.[52]	SS 304	Molybdenum	SV, DS, C, NOD	SR, CS, KW	GRA	It is invented when CS=2.62 mm/min, SR=4.47 µm and KW =0.32 mm then C=3 amp and SV=50 v respectively.

2019	Bhatt and Goyal [10]	SS 304	Copper	T_{on}, T_{off}, WT, SG, WF, GV	MRR, SR	GRA, L24 Array	It is discovered that MRR=3.705 mm^3/min for T_{on} =118 µs, T_{off}=50 µs, WT=10 kg, WF=5 mm/sec and GV=60 v. Whereas SR=0.177 µm for WT=15 kg, GV=40 v, T_{on}=106 µs, T_{off}=60 µs, and WF=2 mm/sec.
2019	Dayakar et.al. [53]	Maraging steel 350	Brass	T_{on}, T_{off}, C, SV	MRR, SR	TT	It is observed that MRR=2.835 mm^3/min for T_{on}=104 µs and C=12 amp. However, C is most effective for finding maximum MRR. SR=1.424 µm when T_{on} =100 µs and C=12 amp.
2020	Kumar et.al.[54]	AISI 630	Molybdenum	C, T_{on}, T_{off}, WF	MRR, SR, TWR	Fuzzy, L9 Array	It is found that MRR=0.119 g/min and SR=2.91 µm when T_{on}=25 µs, T_{off}=7 µs, C=1 amp and WF=4 mm/s respectively.
2021	Biswas et.al.[55]	SS 304	Zinc coated brass	T_{on}, T_{off}, A_{on}, A_{off}, SV, WF	MRR, KW	L27 Array, RSM	It is observed when A_{on}, A_{off}, SV and WF are increased then MRR is increased. KW decreased with lower value of T_{on} and T_{off}.
2022	Boopathi [56]	SS 317	Molybdenum	P, F, C, W	WWR, CR	L27 Array	It is found CR is increased by increasing W, C, and mixing F for

							both processes.
2022	Biswas et. al. [57]	SS 304, SS 316	Zinc coated brass	T_{on}, T_{off}, A_{on}, A_{off}, SV, WF	MRR, KW, OC, R_a	L27 Array, Topsis	It is observed optimum responses are appeared when input parameters values are T_{on} =7 µs, T_{off}=12 µs, A_{on}=6 µs, A_{off}=11µs, WF=6m/min, and SV=60V

6. DISCUSSION

Output variables can be smoothly optimized by proper OT and this review also dealt with low cost, better surface finish and proper dimensional accuracy. Table 6. shows that, lot of researchers used SS 304 as an experimental specimen. Table 7-9 shows previous experimental SR, KW, MRR values of SS 304 with different input variables. Figure 8a-d shows changes of SR with individual input parameters.

Table 7. Various input variables value with minimum SR of SS 304.

Input variables				**Output variable**
T_{on} (µs)	**T_{off} (µs)**	**C (amp)**	**GV (v)**	**SR (µm)**
4.00 [11]	4.00 [15]		60.00 [15]	1.50 [15]
0.29 [41]	4.00 [41]		55.00 [41]	2.02 [41]
14.00 [46]		32.00 [46]		2.15 [46]
0.25 [47]	26.00 [47]		35.00 [47]	1.71 [47]
24.00 [51]		18.00 [51]		2.15 [51]
24.00 [53]	7.00 [53]	6.00 [53]		1.76 [53]
0.35 [54]	15.00 [54]	160.00 [54]	30.00 [54]	1.85 [54]
		3.00 [56]	50.00 [56]	4.47 [56]
106.00 [14]	60.00 [14]		40.00 [14]	0.18 [14]
114.00 [42]	60.00 [42]			1.42 [42]
15.00 [43]	3.00 [43]	2.00 [43]		2.88 [43]
4.00 [49]	4.00 [49]		60.00 [49]	1.50 [49]
5.00 [57]	8.00 [57]		60.00 [57]	1.91 [57]

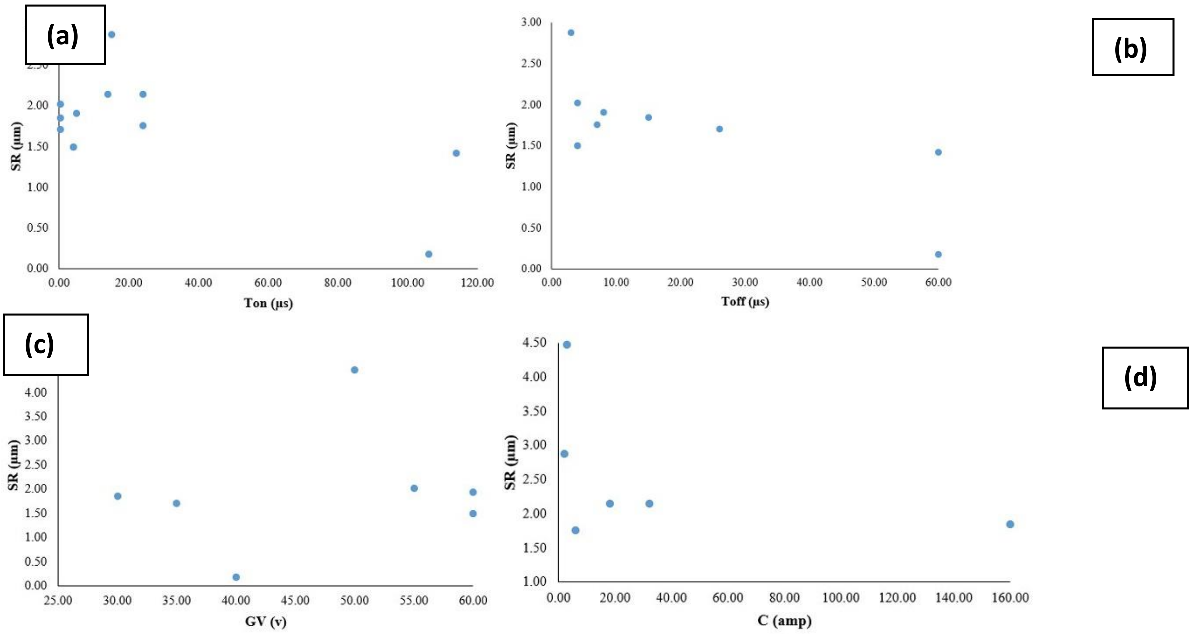
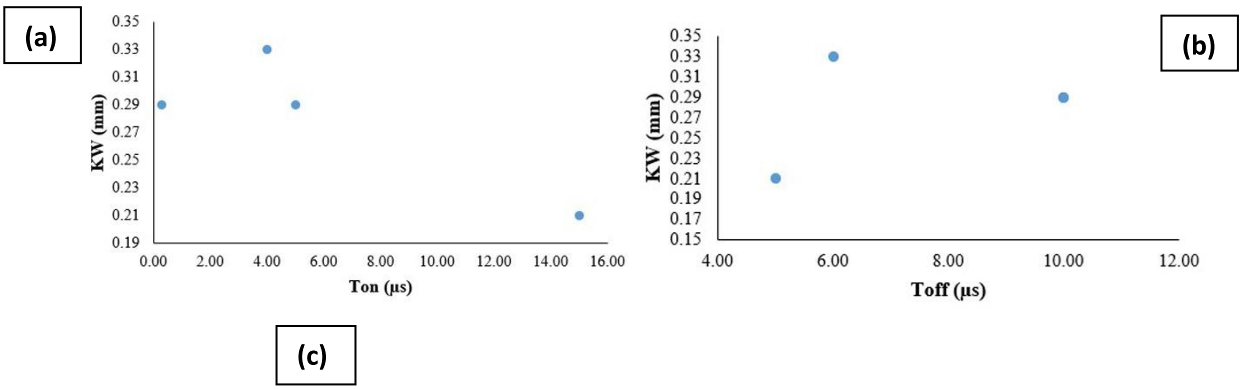


Figure 8. (a) SR Vs T_{on}, (b) SR vs T_{off}, (c) SR vs GV, (d) SR vs C plot for SS 304.

Figure 8a-d. is a graphical representation in between SR Vs T_{on}, T_{off}, GV, C respectively plot for SS 304. It is clear from these plots when T_{on}, T_{off}, and GV are increased then SR also increased. Only C offers higher value gives lower SR values.

Table 8. Various input variables value with minimum KW of SS 304.

Input variables			**Output variables**
T_{on} (µs)	**T_{off} (µs)**	**GV (v)**	**KW (mm)**
4.00 [15]	6.00 [15]	50.00 [15]	0.33 [15]
0.30 [41]	10.00 [41]	40.00 [41]	0.29 [41]
		50.00 [56]	0.32 [56]
15.00 [43]	5.00 [43]		0.21 [43]
5.00 [57]	10.00 [57]	40.00 [57]	0.29 [57]



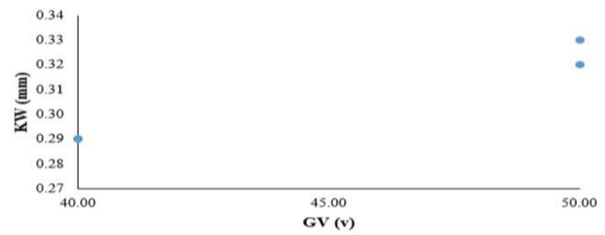


Figure 9. (a) KW vs Ton, (b) KW vs Toff, (c) KW vs GV plot for SS 304

Figure 12. is a graphical representation in between KW vs T_{on}, T_{off} and GV for SS 304. It is shown that to achieved lower KW, required lower T_{on}, T_{off}, and GV values.

Table 9. Various input variables value with maximum MRR of SS 304.

Input variables			**Output variables**
T_{on} (μs)	**T_{off} (μs)**	**GV (v)**	**MRR (mm^3/min)**
6.00 [15]	4.00 [15]	50.00 [15]	51.10 [15]
1.25 [47]	26.00 [47]	15.00 [47]	15.42 [47]
7.00 [50]	17.00 [50]		98.08 [50]
28.00 [53]	5.00 [53]		17.15 [53]
118.00 [14]	50.00 [14]	60.00 [14]	3.71 [14]
125.00 [48]	45.00 [48]		11.18 [48]
35.00 [52]	40.00 [52]		25.23 [52]
9.00 [57]	8.00 [57]	40.00 [57]	6.88 [57]

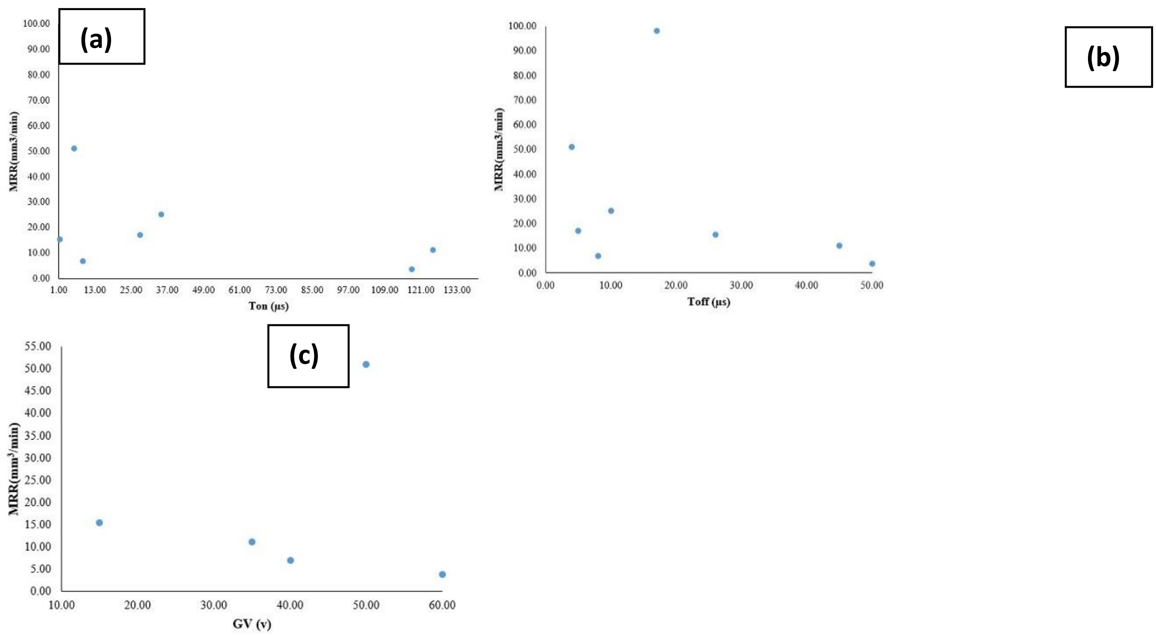


Figure 9. (a) MRR vs T_{on}, (b) MRR vs T_{off}, (c) MRR vs GV plot for SS 304

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 08 | August - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

Figure 9. is a graphical representation in between MRR vs T_{on}, T_{off} and GV for SS 304. It is clear that to achieve higher MRR required moderate T_{on} and T_{off} values and higher GV value.

Table 10 shows the other SS grades (except SS 304) output variables values, which are graphically represented in Figure 10a-b. It is shown that SS 316 shows maximum MRR values respect to Steel 350, on the other hand, steel 350 shows lower SR values compared to others materials.

Table 10. Other SS grades (Except SS 304) MRR and SR values.

SS grade	MRR (mm^3/min)	SR (µm)
SS 316	25.50 [55]	3.20 [55]
Steel 350	2.84 [57]	
SS 420		2.90 [40]
SS 316L		1.54 [45]
SS 302		3.25 [44]
Steel 350		1.28 [57]
AISI 630		2.91 [58]

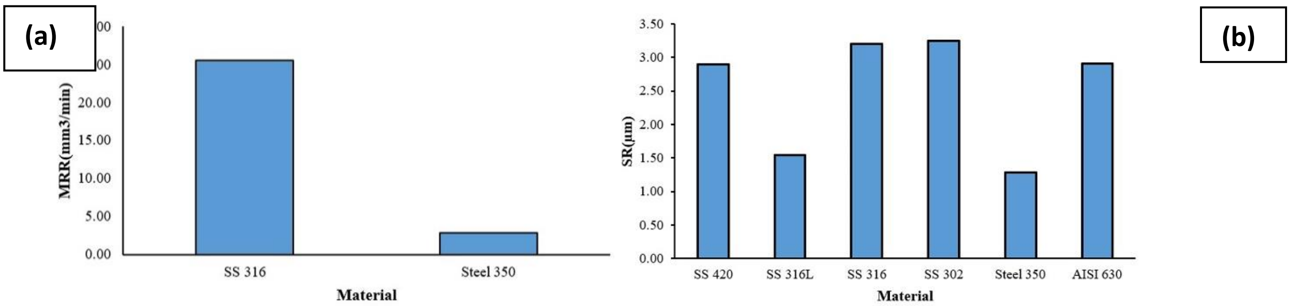


Figure 10. (a) MRR vs SS grades plot, **(b)** SR vs SS grades plot

7. CONCLUSIONS

Present study showed that lots of previous works has been done on WEDM with different SS grades [58,59]. Therefore, it is concluded that the appropriate selection of OT's can save outlays and time both. The list of conclusions are:

- To achieve the maximum MRR, minimum SR and KW, the most effective parameters are T_{on}, T_{off}, C and SV.
- For WEDM, brass wire is rapidly used due to its high tensile strength. Sometimes zinc coated brass wire is also used due to its good tensile strength and proper sparks generation.

- Taguchi Technique (TT) is the best technique compared to other OTs to determine the response parameters when SS 304 and SS 316 are used as work pieces.
- The OA (such as L_{27}, L_{18} etc.) is used to predict the number of experiments. After that ANOVA is used for finding the significant percentage of input variables.
- The main advantage of GRA technique is, its computational divisions are comparatively less complicated respect to another optimization technique's (OT). ANN can operate with incomplete data and it can build a huge number of data. Whereas, fuzzy theory (FT) is used to find the effective of input variable on output variables. Only RSM shows, the relationship between the input variables and responses.

8. FUTURE RESEARCH OPPORTUNITIES

Figure 11 shows future research opportunities on SS machining by WEDM. These opportunities are described below.

- Researchers can use other non-electrical input parameters such as wire diameter, job thickness, dielectric fluid's temperature (water chiller temperature)
- Most experiments have been done using deionized water [60,61]. Therefore, other dielectric fluids (such as normal tap water) which have low viscosity, low cost, less harmful, and adequate cooling rate can be used.
- Maximum works have been done with common SS grades, thus researchers may choose different SS grades.
- Researchers can choose different OT's (such as Tabu search, Artificial bee colony etc.) to find the optimum values of output variables.

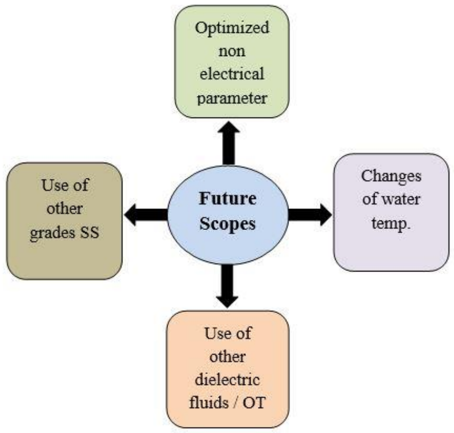


Figure 11. Diagram of future research opportunities on SS

Declarations

Data availability and materials

Since the manuscript already has all the information required to recreate the work, a separate archive is not necessary.

Compliance with ethical standards

The authors state that they are clear of any financial conflicts that have the potential to affect the research presented in this study.

Funding

This research is barred from any funding from any individual, institute, or organization.

Author Contribution

Both authors contributed to the study conception and design. Data collection was performed by [Shatarupa Biswas].

Acknowledgment

Department of Mechanical Engineering, NIT Silchar, India, and CSIR-CMERI, Durgapur, West Bengal, India, are the guiding force behind the creation of this article, the authors are grateful for their valuable contribution.

References

[1] Gowthaman PS, Gowthaman J, Nagasundaram N. A study of machining characteristics of AISI 4340 alloy steel by wire electrical discharge machining process. Mater. Today Proc. 2019;1–6. doi: 10.1016/j.matpr.2019.12.037.

[2] Raju P, Sarcar MMM, Satyanarayana B. Optimization of Wire Electric Discharge Machining Parameters For Surface Roughness On 316L Stailness Steel Using Full Factorial Experimental Design, Procedia Materials Science. 2014;5:1670–1676. doi: 10.1016/j.mspro.2014.07.355.

[3] Dhobe MM, Chopde IK, Gogte CL. Investigations on surface characteristics of heat treated tool steel after wire electro-discharge machining. Mater. Manuf. Process.2013;28:1143–1146. doi: 10.1080/10426914.2013.822976.

[4] Kumar A, Kumar V, Kumar J. Experimental investigation on material transfer mechanism in wedm of pure titanium (Grade-2). Adv. Mater. Sci. Eng.2013;2013:1–21. doi: 10.1155/2013/847876.

[5] Ehsan Asgar M, Singh Singholi AK. Parameter study and optimization of WEDM process: A Review. Materials Science and Engineering. 2018; 404:1–6. doi: 10.1088/1757-899X/404/1/012007.

[6] Sharma N, Khanna R, Gupta R. Multi Quality Characteristics Of WEDM Process Parameters With RSM. Procedia Engineering, 2013; 64: 710–719. doi: 10.1016/j.proeng.2013.09.146.

[7] Kumar A, Kumar V, Kumar J. Investigation of machining characterization for wire wear ratio & MRR on pure titanium in WEDM process through response surface methodology. J. Process Mech. Eng.2018; 232:108–126. doi: 10.1177/0954408916685588.

[8] Chaudhary T, Siddiquee AN, Chanda AK. Effect of wire tension on different output responses during wire electric discharge machining on AISI 304 stainless steel. Def. Technol.2019;15(4): 541–544. doi: 10.1016/j.dt.2018.11.003.

[9] Ho KH, Newman ST, Rahimifard S, Allen RD. State of the art in wire electrical discharge machining (WEDM). Int. J. Mach. Tools Manuf. 2004; 44(12–13):1247–1259. doi: 10.1016/j.ijmachtools.2004.04.017.

[10]Bhatt D, Goyal A. Multi-objective optimization of machining parameters in wire EDM for AISI-304. Mater. Today Proc.2019;18: 4227–4242. doi: 10.1016/j.matpr.2019.07.381.

[11]Lingadurai K, Nagasivamuni B, Muthu Kamatchi M, Palavesam J. Selection of Wire Electrical Discharge Machining Process Parameters on Stainless Steel AISI Grade-304 using Design of Experiments Approach. J. Inst. Eng. Ser. C. 2012; 93(2):163–170. doi: 10.1007/s40032-012-0020-6.

[12]Kalpakjian S, Schmid SR. Manufacturing Processes for Engineering Materials - Solution Manual. 2008.

[13]Kaladhar M, Venkata Subbaiah K, Rao CHS. Machining of austenitic stainless steels - A review. Int. J. Mach. Mach. Mater.2012;12(1–2):178–192. doi: 10.1504/IJMMM.2012.048564.

[14]Huang CA, Hsu FY, Yao SJ. Microstructure analysis of the martensitic stainless steel surface fine-cut by the wire electrode discharge machining (WEDM). Mater. Sci. Eng. A. 2004;371:119–126. doi: 10.1016/j.msea.2003.10.277.

[15]Pramanik A, Basak AK, Dixit AR, Chattopadhyaya S. Processing of duplex stainless steel by WEDM. Mater. Manuf. Process. 2018:1–11. doi: 10.1080/10426914.2018.1453165.

[16]Gowthaman PS, Jeyakumar S, Saravanan BA. Machinability and tool wear mechanism of Duplex stainless steel - a review. Mater. Today Proc. 2019;1–7. doi: 10.1016/j.matpr.2020.02.295.

[17]Kazior J, Szewczyk-Nykiel A, Pieczonka T, Hebda M, Nykiel M. Properties of precipitation hardening 17-4 PH stainless steel manufactured by powder metallurgy technology. Adv. Mater. Res.2013; 811: 87–92. doi: 10.4028/www.scientific.net/AMR.811.87.

[18]Bisaria H, Shandilya P. The machining characteristics and surface integrity of Ni-rich NiTi shape memory alloy using wire electric discharge machining. J. Mech. Eng. Sci.2019;1–11. doi: 10.1177/0954406218763447.

[19]Soundararajan R, Ramesh A, Mohanraj N, Parthasarathi N. An investigation of material removal rate and surface roughness of squeeze casted A413 alloy on WEDM by multi responce optimization using RSM. J. Alloys Compd. 2016. doi: 10.1016/j.jallcom.2016.05.292.

[20]Choudhuri B, Sen R, Ghosh SK, Saha SC. Comparative machinability characterization of wire electrical discharge machining on different specialized AISI steels. Bull. Mater. Sci.2020;1–12. doi: 10.1007/s12034-019-1982-2.

[21]Venkatarao K, Kumar TA. An experimental parametric analysis on performance characteristics in wire electric discharge machining of Inconel 718. J. Mech. Eng. Sci. 2019;1–14. doi: 10.1177/0954406219840677.

[22]Banu A, Abu Bakar M, Ali MY, Adesta YET. Analysis of WEDM Process Parameters on Surface Roughness and Kerf using Taguchi Method. Int. J. Eng. Mater. Manuf. 2017; 2(4):103–109. doi: 10.26776/ijemm.02.04.2017.04.

[23]Rao SSM, Rao KV, Reddy KH, Rao CVSP. Prediction and optimization of process parameters in wire cut electric discharge machining for high-speed steel (HSS). Int. J. Comput. Appl. 2017;39:1–9. doi: 10.1080/1206212X.2017.1309219.

[24]Mahdieh MS, Mahdavinejad RA. A study of stored energy in ultra-fined grained aluminum machined by electrical discharge machining. J. Mech. Eng. Sci.2017:1–9. doi: 10.1177/0954406216666872.

[25]Pitayachaval P, Jittamai P, Baothong T. A review of machining parameters that effect to wire electrode wear. 4th International Conference on Industrial Engineering and Applications. 2017;1–4, doi: 10.1109/IEA.2017.7939167.

[26]Debnath T, Patowari PK. Fabrication of an array of micro-fins using Wire-EDM and its parametric analysis. Mater. Manuf. Process. 2018;1–10. doi: 10.1080/10426914.2019.1566959.

[27]Noor Zaman Khan ZAK, Wahid MA, Singh S, Siddiquee AN. A Study on Micro Hardness in Wire Electrical Discharge Machining Based on Taguchi Method. Int. J. Mech. Prod. Eng. 2013;1:10–15.

[28]Sharma P, Chakradhar D, Narendranath S. Evaluation of WEDM performance characteristics of Inconel 706 for turbine disk application. Mater. Des. 2015;1–19. doi: 10.1016/j.matdes.2015.09.036.

[29]Faisal N, Kumar K. Optimization of Machine Process Parameters in EDM for EN 31 Using Evolutionary Optimization Techniques. Technologies. 2018; 6:54. doi: 10.3390/technologies6020054.

[30]Upadhyay BBC, Rahul , Datta S, Mahapatra SS. An experimental investigation on electro discharge machining of Inconel 601. Int. J. Ind. Syst. Eng.2018; 29(2): 223–251.

[31]Choudhary SK, Jadoun RS, Kumar A. Latest Research Trend of optimization Techniques in Electric Discharge Machining (EDM): Review Article. Int. J. Res. Eng. Adv. Technol.2014; 2(3):1–29.

[32]Gangil M, Pradhan MK, Purohit R. Review on modelling and optimization of electrical discharge

machining process using modern Techniques. Materials Today: Proceedings. 2017; 4:2048–2057. doi: 10.1016/j.matpr.2017.02.050.

[33]Dreyfus SE. The Computational Solution of Optimal Control Problems with Time Lag. IEEE Trans. Automat. Contr.1973;18(4):383–385. doi: 10.1109/TAC.1973.1100330.

[34]Haykin S. Neural Networks and Learning Machines. 1999.

[35]Deshmukh SS, Zubair AS, Jadhav VS, Shrivastava R. Optimization of process parameters of wire electric discharge machining on AISI 4140 using taguchi method and grey relational analysis. Materials Today: Proceedings.2019;18:4261–4270. doi: 10.1016/j.matpr.2019.07.384.

[36]Thankachan T *et al.*, Prediction of surface roughness and material removal rate in wire electrical discharge machining on aluminum based alloys/composites using Taguchi coupled Grey Relational Analysis and Artificial Neural Networks. Appl. Surf. Sci. 2019; 472:22–35. doi: 10.1016/j.apsusc.2018.06.117.

[37]Durairaj M, Sudharsun D, Swamynathan N. Analysis of process parameters in wire EDM with stainless steel using single objective Taguchi method and multi objective grey relational grade. Procedia Eng.2013;64:868–877. doi: 10.1016/j.proeng.2013.09.163.

[38]Geetha M, Sreenivasulu B, Gowd GH. Modeling & Analysis of performance characteristics of Wire EDM of SS304. Int. J. Innov. Technol. Explor. Eng.2013;3(4): 122–125.

[39]Khan ZA, Siddiquee AN, Khan NZ, Khan U, Quadir GA. Multi Response Optimization of Wire Electrical Discharge Machining Process Parameters Using Taguchi based Grey Relational Analysis. Procedia Mater. Sci.2014; 6:1683–1695. doi: 10.1016/j.mspro.2014.07.154.

[40]Paliwal S, Solanki P, Soni M, Chanda AK. Parameter Optimization of Wire Electrical Discharge Machining for Minimum Surface Roughness and Kerf Width using Taguchi Method. Int. J. Ind. Electron. Electr. Eng.2014; 2(7): 36–39.

[41]Raju P, Sarcar MMM, Satyanarayana B. Optimization of Wire Electric Discharge Machining Parameters for Surface Roughness on 316 L Stainless Steel Using Full Factorial Experimental Design. Procedia Mater. Sci.2014;5:1670–1676. doi: 10.1016/j.mspro.2014.07.355.

[42]Nayak BB, Mahaparta SS. A Utility Concept Approach for Multi-objective optimization of Taper Cutting Operation using WEDM. Procedia Engineering. 2014;97: 469–478, doi: 10.1016/j.proeng.2014.12.271.

[43]Mathew B, Benkim, Babu J. Multiple Process parameter Optimization of WEDM on AISI304 Using Taguchi Gray Relational Analysis. Procedia Materials Science. 2014; 5:1613–1622. doi: 10.1016/j.mspro.2014.07.349.

[44]Kumar S, Garg SK, Chawla G. Experimental Investigation of Effect of Process Parameters on Material

Removal Rate during WEDM. Int. J. Curr. Eng. Technol.2016; 6(1): 40–45.

[45]Bharathi P, Gouri T, Priyanka L, Rao GS, Rao BN. Optimum WEDM Process Parameters of SS304 Using Taguchi Method. Int. J. Ind. Manuf. Syst. Eng.2016;1(3): 69–72. doi: 10.11648/j.ijimse.20160103.15.

[46]Suresh T, Aruneash P, Gunasekar S, Janakiraman B. Comparison of Brass and Zinc Coated Wire Electrode Using Wire Cut EDM Concerning MRR of Machining SS304. Int. J. Innov. Res. Sci. Eng. Technol.2017; 6(3):4970–4976. doi: 10.15680/IJIRSET.2017.0603295.

[47]Nayak BB, Mahapatra SS. An intelligent approach for multi-response optimisation of WEDM parameteres. Int.J. Ind. Syst. Eng.2017;25(2):197–227.

[48]Babu TV, Subbaratnam B. Experimental investigation of Wire Electrical Discharge Machining (WEDM) Process Parameters on SS304 using Taguchi method. Int. J. Curr. Eng. Technol.2018;8:0–3. doi: 10.14741/ijcet/v.8.3.2.

[49]Ugrasen G, Singh MRB, Ravindra HV. Optimization of Process Parameters for SS304 in Wire Electrical Discharge Machining using Taguchi's Technique. Mater. Today Proc.2018; 5(1): 2877–2883. doi: 10.1016/j.matpr.2018.01.080.

[50]Choudhuri B, Sen R, Ghosh SK, Saha SC. Study of surface integrity and recast surface machined by Wire electrical discharge machining. Materials Today: Proceedings. 2018;5:7515–7524. doi: 10.1016/j.matpr.2017.11.423.

[51]Padmavathi KR, Devaraj IS, Solomon J, Premkumar A. Influence of Process Parameters on Wire EDM Process for AISI 316 Stainless Steel. Int. J. Eng. Res. Technol.2018; 6(2):1–6. doi: 10.17577/ijertcon067.

[52]Ishfaq K, Ahmad N, Jawad M, Ali MA, Al-Ahmari AM. Evaluating material's interaction in wire electrical discharge machining of stainless steel (304) for simultaneous optimization of conflicting responses. Materials (Basel).2019;12: 1–15. doi: 10.3390/ma12121940.

[53]Dayakar K, Raju KVMK, Raju CRB. Prediction and optimization of surface roughness and MRR in wire EDM of maraging steel 350. Mater. Today Proc.2019;18:2123–2131. doi: 10.1016/j.matpr.2019.06.635.

[54]Kumar J, Soota T, Rajput SK. Experimental evaluation and modelling of wire-EDM process parameter for stainless steel AISI 630. Mater. Today Proc.2020: 2–9. doi: 10.1016/j.matpr.2020.02.231.

[55]Biswas S, Sing Y, Mukhejee M. Optimization of MRR and KW of SS 304 in Wire EDM by RSM Technique. Recent Adv. Mech. Eng. Lect. Notes Mech. Eng.2021: 57–68.

[56]Boopathi S. Cryogenically treated and untreated stainless steel grade 317 in sustainable wire electrical discharge machining process: a comparative study. Environ. Sci. Pollut. Res.2022:1–10. doi: 10.1007/s11356-022-22843-x.

[57]Biswas S, Singh Y, Mukherjee M, Datta S, Barman S, Raja M. Design of Multi-material Model for Wire Electro-discharge Machining of SS304 and SS316 Using Machine Learning and MCDM Techniques. Arab. J. Sci. Eng.2022. doi: 10.1007/s13369-022-06757-x.

[58] Biswas S, Singh Y, Mukherjee. A Study on Austenitic Stainless Steel Machining by Wire EDM. Springer, icadma, MNIT Jaipur, 2020.

[59] Biswas S, Singh Y, Mukherjee. An Overview of Wire Electrical Discharge Machining, Springer, Icrame, NIT Silchar, 2020.

[60] Biswas S, Paul AR, Dhar AR, Singh Y, Mukherjee M. 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 2023; 41: 350–364. https://doi.org/10.1016/j.cirpj.2022.12.005.

[61] Biswas S, Mukherjee. Uses of Various Dielectrics in Electro Discharge Machining (EDM) – A Critical Review. International Journal of Innovative Science and Research Technology.2023; 8(6):2174-2194. Doi.10.5281/zenodo.8133478.