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Procedia Materials Science 5 (2014) 1613 – 1622
Procedia Materials Science
www.elsevier.com/locate/procedia

International Conference on Advances in Manufacturing and Materials Engineering, AMME 2014

Multiple Process Parameter Optimization of WEDM on AISI304 Using Taguchi Grey Relational Analysis

BijoMathew[a], Benkim[a], J.Babu[a]*

[a]*Department of Mechanical Engineering, St.Joseph' College of Engineering&Technology, Choonadacherry, Palai-686579, Kerala, India*

Abstract

Wire electric discharge machining (WEDM) is an indispensable machining technique for producing complicated cut-outs through difficult to machine metals without using high cost grinding or expensive formed tools. This paper presents, an effective Taguchi grey relational analysis applied to experimental results of WEDM on AISI304 considering multiple output responses. The objective of this study is to obtain improved material removal rate, surface finish and reduce the dimensional deviation. The experiment has been done using Taguchi orthogonal array L_{27}. Each experiment was carried out with different conditions of input parameters. The input parameters used for optimization are pulse on time, pulse off time, servo voltage, wire feed, wire tension, and di-electric pressure. The response table and grey relation grade for each level of machining parameters were established and the best combination of parameters was obtained by Taguchi grey relational analysis. The results revealed thatoptimum combination of process parameters for multi process parameter optimization, by using grey relational analysis was of, pulse on time level1,pulse off time level 2, servo voltage level1, water pressure level3, wire feed level3 and wire tension level 3.

Selection and peer-review under responsibility of Organizing Committee of AMME 2014

*Keywords:*Taguchi's L_{27} orthogonal array; WEDM; Material removal rate; Surface finish; Dimensional deviation; Grey relational analysis

1. Introduction.

As newer and more exotic materials have been developed in the past few decades, conventional machining operations tend to reach their limitations as relatively more complicated shaped jobs are required to be manufactured. Wire EDM provides the best alternative of conventional machining operations. Also it is a fact that because of the many variables and the complex nature of the process, optimization of variables is needed to achieve

* Corresponding author. Tel.: +91-860-655-7396.
E-mail address: jsnebankni@yahoo.co.in

2211-8128
Selection and peer-review under responsibility of Organizing Committee of AMME 2014
doi:10.1016/j.mspro.2014.07.349

optimal performance. Several researchers attempted to predict the optimal parameters to achieve the performance measure at optimal level. Puri and Bhattacharyya (2003) employed Taguchi methodology involving thirteen control factors with three levels for an orthogonal array L_{27} (3^{13}) to find out the main parameters that affect the different machining criteria, such as average cutting speed, surface roughness values and the geometrical inaccuracy caused due to wire lag.

Nomenclature

AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
T on	Pulse On time
T off	Pulse Off time
SV	Servo voltage
WP	Water Pressure
WF	Wire Feed
WT	Wire Tension
MRR	Material Removal Rate
SR	Surface Roughness
DD	Dimensional Deviation

Liao and Yu (2004) used specific discharge energy (SDE) concept in WEDM. Experimental results revealed that the relative relationship of SDE between different materials is invariant as long as all materials are machined under the same machining conditions.Yan and Tsai (2004) conducted their work on Al_2O_3/6061Al composites in the experiment. Machining parameters of pulse on time were changed to explore their effects on machining performance, including the cutting speed, the width of slit and surface roughness. It is revealed that, a very low wire tension, a high flushing rate and a high wire speed are required to prevent wire breakage. Hewidy and Taweel(2005) developed mathematical models for correlating the inter relationships of various WEDM machining parameters of Inconel 601 material such as: peak current, duty factor, wire tension and water pressure on the MRR ,wear ratio and surface roughness. This work was based on response surface methodology. They found out a linear relationship of peak current with wear ratio.

Milleret.al, (2005) investigated effects of spark cycle and pulse on-time on wire EDM micro features. Tests were conducted on various materials viz. Nd–Fe–B magnetic material, carbon bipolar plate, and titanium for wire EDM cutting of minimum cross section thickness. A hypothesis was proposed based on the combined thermal and electrostatic force to cause the fracture of thin-section during wire EDM. This was supported by findings from SEM micrographs of EDM surface, subsurface and debris. Sarkar et.al, (2005) performed experiments using γ-titanium aluminide alloy as work material and then formulated mathematical models to predict the cutting speed, surface finish and dimensional deviation as the function of different control parameters. They determined the optimal process parameters by applying constrained optimization technique in which one performance characteristic was optimized considering others as constraints. Aminollah and Alireza (2008) used cylindrical forms of hard to machine materials for their experiment. At first they designed a precise, flexible and corrosion resistant rotary spindle to rotate the work piece to generate free form cylindrical geometries. It was found thatpower, voltage and servo were the most significant parameters among their selected ones.Ramakrishnan and Karunamoorthy (2008) developed artificial neural network (ANN) models and multi response optimization technique to predict and select the best cutting parameters of wire electro-discharge machining (WEDM) process. The efficiency of wire electrical discharge machining of hard- to-machine materials was investigated experimentally by DarriusPoros et.al.,(2008).In his experiment, titanium alloys and cemented carbide were machined. Vinod Kumar,et.al, (2012) investigated the effects of WEDM parameters on machinability of nimonic-90.Based on the experimentation WEDM parameters namely discharge current, pulse on time and pulse off time produced highly noticeable effects on cutting speed.BhaskaraReddy et.al, (2012) conducted experiments on wire EDM considering two different materials for same parametric values and compared the performance characteristics in terms of MRR and Surface roughness. Parameters selected were pulse on time, pulse off time, bed speed and current and found that major influencing factor was current. Based on the results, it was recommended that the EN 19 material suitable for better MRR.Then the SS 420 material was recommended to obtain better surface. Basil and Joseph Kunju (2012) conducted experiments in 3l Electronic ultra-cut S1 machine using 0.25 mm brass wire as electrode. Pulse on time, pulse off time, voltage and water pressure were the four parameters selected for investigation. The pulse on time and dielectric water pressure were found to be the most significant factors on the surface roughness value.

Y.M Puri and Deshpande (2004) described the multi objective optimization of the WEDM process using parametric design of Taguchi methodology. The effect of various machining parameters such as gap voltage, gap current, duty factor and wire feed were studied in machining of High Carbon High Chromium die steel plate. It was identified that the gap current and gap voltage had more influence than the other parameters. Moreover, the multiple performance characteristics such as material removal rate and surface roughness for the WEDM process could be improved by setting the various process parameters at their optimal levels.Rajyalakshmi and VekataRamaiah (2013) conducted experiments with eight process parameters: pulse on time, pulse off time, corner servo voltage, wire feed, wire tension, dielectric flow rate, spark gap voltage and servo feed to be varied in three different levels. Grey relational analysis was carried out and found pulse on time was the major influencing factor for MRR, surface roughness and spark gap.RohitGarg (2010) conducted experiment on H-11 hot die steel plate and found out the influencing parameters for responses by using utility concept. Results revealed that pulse on time, pulse off time and peak current were the significant parameters. It is found from the literature very few authors conducted optimisation in machining of AISI304 Stainless steel with multi-objective function using grey relational analysis. This paper presents optimization of WEDM of AISI304 using Taguchi-based grey Relation Analysis (TGRA).

2. Materials and methods

2.1. Material and experimental setup

Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts of hard materials with complex shapes. Parts having sharp edges that pose difficulties to be machined by the main stream machining process can be easily machined by WEDM process. The AISI 304 material of 600 mm x 25mm x 10mm size has been used as a work piece material for the present experiments. The selection of the AISI 304 stainless steel was made taking into account its use in almost all industrial applications for approximately 50% of the world's stainless steel production and consumption. It has wide range of applications in the area of wire EDM. It has varied practical applications in the manufacturing of components used in cryogenic vessels, evaporators, hospital surgical equipment, marine equipment, fasteners, nuclear vessels, feed water tubing, valves, refrigeration equipment, etc. The chemical composition of this material AISI 304 is given in Table 1. The WEDM experiments were conducted in Electronica ultra- cut S1 machine ofElectronica Machine Tools Ltd. installed at Keltron Tool room Research and Training centre, Aroor, Kerala using 0.25 mm brass wire as the tool electrode and deionized water as dielectric fluid. Pulse on time, pulse off time, Servo voltage, dielectric pressure, wire feed and wire tension were the six WEDM parametersselected for investigations. All other machine parameters were kept constant during the time of experiment.Cutting rate was digitally displayed on the screen of the machine and is given quantitatively in mm/minute;the surface roughness was measured by MitutoyoSurftest SJ-201P.The specimen cross-section is measured with the help of a Mitutoyo's digital micrometer having the least count of 0.001 mm and the deviation of the measured dimension was calculated in percentage using the following expression:
Dimensional deviation=[(Observed value – Actual value) / Actual value

Material removal rate was calculated by using the following expression:
MRR=cutting rate×kerf width×height

Table .1: Chemical composition of AISI304

Element	Carbon (C)	Chromium (Cr)	Manganese (Mn)	Nickel (Ni)	Phosphorous (P)	Sulphur (S)	Silicon (Si)	Ferrous (Fe)
Content (%)	0.08	18.5	1.9	8.4	0.026	0.016	0.4	Balance

2.2. Design of experiments.

Taguchi method was applied to plan the experiments, Gadakh.V.S, (2012). For the present experimental work the six process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behaviour of output parameters of study. The process parameters and the levels selected for this is listed in table2.The experimental design was according to an L_{27} array based on Taguchi method (Table 3). Minitab software was used for Taguchi analysis.

Table.2. Input Parameters and Levels

Parameter	Symbol	Level 1		Level 2		Level 3	
		Machine unit	Actual value	Machine unit	Actual value	Machine unit	Actual value
Pulse on Time, µs	A	103	0.25	113	0.75	123	1.25
Pulse off time, µs	B	50	26	55	36	60	46
Servo voltage, V	C	----	15	----	25	----	35
Di-electric pressure, Kg/cm^2	D	----	9	----	12	----	15
Wire feed ,m/min	E	----	4	----	7	----	10
Wire tension, N	F	5	5.88	8	9.8	11	15.68

Table.3.Experimental Design Taguchi L_{27}

Experiment No.	T on	T off	SV	WP	WF	WT
1	1	1	1	1	1	1
2	1	1	2	2	2	2
3	1	1	3	3	3	3
4	1	2	1	2	2	3
5	1	2	2	3	3	1
6	1	2	3	1	1	2
7	1	3	1	3	3	2
8	1	3	2	1	1	3
9	1	3	3	2	2	1
10	2	1	1	2	3	2
11	2	1	2	3	1	3
12	2	1	3	1	2	1
13	2	2	1	3	1	1
14	2	2	2	1	2	2
15	2	2	3	2	3	3
16	2	3	1	1	2	3
17	2	3	2	2	3	1
18	2	3	3	3	1	2
19	3	1	1	3	2	3
20	3	1	2	1	3	1
21	3	1	3	2	1	2
22	3	2	1	1	3	2
23	3	2	2	2	1	3
24	3	2	3	3	2	1
25	3	3	1	2	1	1
26	3	3	2	3	2	2
27	3	3	3	1	3	3

2.3. Taguchi optimization method and grey relation method of multi optimization.

In the Taguchi method, S/N ratio is the measure of quality characteristics and deviation from the desired value.S/N ratios were determined for material removal ratelarger –is- the- better criterionby using equation. (1),for surface roughness and dimensional deviation the –smaller- is- the -better criterionby usingequation(2).

$$\frac{S}{N} = -\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2} \quad ---- (1)$$

$$\frac{S}{N} = -\log\frac{1}{n}\sum_{i=1}^{n}y^2 \quad ------- (2)$$

Grey relational analysis has been widely used to convert multiple objective optimisation problems in to a single equivalent objective function. The steps in grey relational analysis are:Grey Relation Normalisation; Determination of deviation; Calculation of Grey Relational Coefficient(GRC);Determination of Grey Relational Grade (GRG); Determination of optimum parameters; G.Rajyalaxmi et.al. (2013)

3. Results and discussions

The experimental results for material removal rate, surface roughness and dimensional deviation are given in Table.4. 27 experiments were conducted to prepare 27 square punches of size 10×10 mm, shown in Fig. 1. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software.

Table. 4.Experimental layout using an L27 orthogonal array and experimental results

Experiment No.	T on	T off	SV	WP	WF	WT	MRR (mm^3/min)	SR (μm)	DD (mm)
1	1	1	1	1	1	1	3.780	2.05	0.86
2	1	1	2	2	2	2	5.656	2.01	0.94
3	1	1	3	3	3	3	5.490	1.71	0.75
4	1	2	1	2	2	3	5.722	1.96	0.525
5	1	2	2	3	3	1	5.487	1.867	0.585
6	1	2	3	1	1	2	4.318	1.98	0.75
7	1	3	1	3	3	2	5.155	1.76	0.505
8	1	3	2	1	1	3	5.098	2.235	0.79
9	1	3	3	2	2	1	4.780	1.882	0.84
10	2	1	1	2	3	2	9.797	3.867	0.99
11	2	1	2	3	1	3	9.890	3.152	0.9
12	2	1	3	1	2	1	7.762	3.32	0.95
13	2	2	1	3	1	1	8.75	3.15	0.46
14	2	2	2	1	2	2	9.19	3.35	0.93
15	2	2	3	2	3	3	7.801	2.869	0.55
16	2	3	1	1	2	3	8.2144	3.315	0.66
17	2	3	2	2	3	1	9.735	3.18	0.97
18	2	3	3	3	1	2	8.03	2.98	0.598
19	3	1	1	3	2	3	15.423	3.29	1.41
20	3	1	2	1	3	1	14.223	3.68	1.68
21	3	1	3	2	1	2	14.065	3.59	1.18
22	3	2	1	1	3	2	13.674	3.63	1.01
23	3	2	2	2	1	3	13.981	3.5	1.05
24	3	2	3	3	2	1	12.954	3.15	0.937
25	3	3	1	2	1	1	9.345	2.89	0.605
26	3	3	2	3	2	2	10.6565	3.54	0.823
27	3	3	3	1	3	3	9.1534	3.487	0.99

Fig.1. Square punches of 10×10 mm

Table.5. S/N ratio values for the experimental results

Experiment No.	T on	T off	SV	WP	WF	WT	S/N ratio, MRR	S/N ratio, SR	S/N ratio DD
1	1	1	1	1	1	1	11.503	-6.235	1.310
2	1	1	2	2	2	2	15.041	-6.063	0.537
3	1	1	3	3	3	3	14.791	-4.659	2.498
4	1	2	1	2	2	3	15.147	-5.845	5.596
5	1	2	2	3	3	1	14.775	-5.422	4.656
6	1	2	3	1	1	2	12.689	-5.933	2.498
7	1	3	1	3	3	2	14.236	-4.910	5.934
8	1	3	2	1	1	3	14.134	-6.985	2.047
9	1	3	3	2	2	1	13.588	-5.492	1.514
10	2	1	1	2	3	2	19.821	-11.747	0.087
11	2	1	2	3	1	3	19.903	-9.971	0.915
12	2	1	3	1	2	1	17.799	-10.423	0.445
13	2	2	1	3	1	1	18.840	-9.966	6.744
14	2	2	2	1	2	2	19.266	-10.501	0.630
15	2	2	3	2	3	3	17.843	-9.154	5.192
16	2	3	1	1	2	3	18.291	-10.410	3.609
17	2	3	2	2	3	1	19.766	-10.049	0.264
18	2	3	3	3	1	2	18.094	-9.484	4.465
19	3	1	1	3	2	3	23.763	-10.344	-2.984
20	3	1	2	1	3	1	23.059	-11.317	-4.506
21	3	1	3	2	1	2	22.962	-11.102	-1.437
22	3	2	1	1	3	2	22.717	-11.198	-0.086
23	3	2	2	2	1	3	22.910	-10.881	-0.423
24	3	2	3	3	2	1	22.248	-9.966	0.565
25	3	3	1	2	1	1	19.411	-9.218	4.364
26	3	3	2	3	2	2	20.552	-10.980	1.692
27	3	3	3	1	3	3	19.231	-10.849	0.087

3.1. Effect of process parameters on material removal rate.

The material removal rate increases with the increase in pulse on time. This is because the discharge energy increases with the pulse on time. This is because the discharge energy increases with the pulse on time. As the pulse off time decreases, the number of discharges within a given period becomes more which leads to a higher cutting rate. When servo voltage increases from 15 V to 25 V MRR shows the increasing trend. But further increase of servo voltage results in the decrease of MRR. Large servo voltage means large ionization of the dielectric fluid between work piece and wire electrode which results in high discharge energy per spark, favours high MRR.But further increase of servo voltage from 25 V, not favouring in the material removal rate as the large amount of debris is unable to clear off the gap for a given pulse off time. The increasing of water pressure decreases the tendency for arcing, and there by increases the material removal rate. It is also shown that, MRR increases with wire feed and wire tension, but these effects are not significant. The trend of parameter levels are in agreement with the findings of Vinod Kumar et.al. (2008)

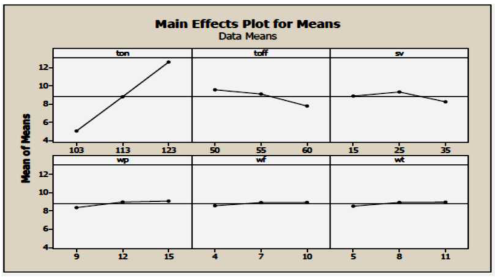

Fig.2. Effect of process parameters on MRR

As material removal rate is the "higher the better" type quality characteristic, it can be seen from Fig 2, that the third level of pulse on time (A3), first level of pulse off time (B1), second level of servo voltage (C2), third level of water pressure (D3), third level of wire feed (E3) and third level of wire tension (F3) provide maximum value of MRR.

3.2. Effect of process parameters on surface finish.

Surface roughness (SR) increases with the increase of pulse on time and decreases with increase in pulse off time and water pressure. As the pulse off time decreases, the number of discharges increases which causes poor surface accuracy. As the water pressure increases, better removals of debris takes place in between work piece and wire electrode, which results in the improvement of surface finish. When servo voltage increases from 15 V to 25 V, surface roughness also increases because of high discharge energy per spark, which makes the surface rough. But further increase of servo voltage reduces roughness value. The reason is when servo voltage exceeds a certain value; the average discharge gap gets widened resulting into better surface accuracy due to stable machining .When wire tension increases, roughness value increases first and then decreases. The effects of wire feed are not very significant for surface roughness. The trends of most parameters levels are in agreement with the findings of Sarkar and Mitra (2005).

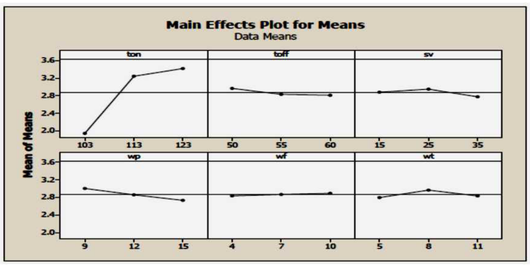

Fig.3. Effect of process parameters on SR

As surface roughness is the "lower the better" type quality characteristic, from Fig. 3, it can be seen that the first level of pulse on time (A1), third level of pulse off time (B3), third level of servo voltage (C3), third level of water pressure (D3), first level of wire feed (E1) and first level of wire tension (F1) result in minimum value of surface roughness

3.3. Effect of process parameters on dimensional deviation

Dimensional deviation (DD) increases with increase in pulse on time. As pulse off time increases, the dimensional deviation decreases. With the increase in water pressure decrement in the value of dimensional deviation is observed. Dimensional deviation increases with increase in servo voltage first and then decreases. Increasing wire feed value leads to higher dimensional deviation. But increase in wire tension leads to lowers the value.

Dimensional deviation value increases if the energy contained in a pulse increases to a large value. That's why when pulse on time is very high the dimensional deviation increases. The trends of most of parameter values support the findings made by Sarkar and Mitra (2005).

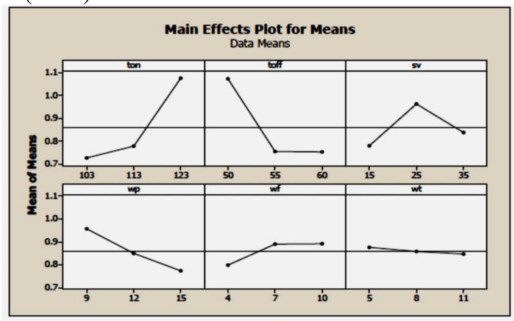

Fig.4. Effect of process parameters on DD

As dimensional deviation is the "lower the better" type quality characteristic, from Fig.4, it can be seen that the first level of pulse on time (A1), third level of pulse off time (B3), first level of servo voltage (C1), third level of water pressure (D1), first level of wire feed (E1) and third level of wire tension (F3) provide minimum value of dimensional deviation.

3.4. Grey relational analysis.

Grey relational analysiswas carried by following the steps mentioned in the section 2.4. The grey relational coefficients and the grey relation grade and SN ratio of grey relation grade, considering the larger- is- the-betterwere calculated and tabulated in table6. The main effect plot for means and SN ratio of grey relation grade are shown in Fig.5.

Table.6 Grey relational coefficient and grey grade.

Experimental number	Grey relational coefficient			Grey relational grade	SN ratio for Grey relation grade
	MRR	SR	DD		
1	0.3333	0.7602	0.6039	0.5658	-4.9467
2	0.3733	0.7823	0.5595	0.5717	-4.8566
3	0.3694	1	0.6776	0.6823	-3.3205
4	0.3749	0.8116	0.9036	0.6967	-3.1391
5	0.3692	0.8729	0.8298	0.6906	-3.2155
6	0.3437	0.7997	0.6776	0.6070	-4.3362
7	0.3616	0.9556	0.9312	0.7494	-2.5057
8	0.3603	0.6725	0.6489	0.5605	-5.0285
9	0.3535	0.8623	0.6161	0.6106	-4.2849
10	0.5084	0.3333	0.535	0.4589	-6.7656
11	0.5126	0.4278	0.5809	0.5071	-5.8981
12	0.4317	0.4011	0.5545	0.4624	-6.6996
13	0.4658	0.4282	1	0.6313	-3.9953
14	0.4829	0.3966	0.5647	0.4814	-6.3499
15	0.433	0.4819	0.8713	0.5954	-4.5038
16	0.4467	0.4018	0.753	0.5338	-5.4524
17	0.5067	0.4231	0.5446	0.4914	-6.1713
18	0.4405	0.4592	0.8153	0.5716	-4.8582
19	1	0.4056	0.391	0.5988	-4.4544
20	0.829	0.3537	0.3333	0.5053	-5.9290
21	0.8107	0.3645	0.4586	0.5446	-5.2785
22	0.7688	0.3596	0.5258	0.5514	-5.1707
23	0.8014	0.3759	0.5082	0.5618	-5.0084
24	0.7021	0.4282	0.5611	0.5638	-4.9775
25	0.4891	0.4775	0.8085	0.5917	-4.5580
26	0.5494	0.3707	0.6268	0.5156	-5.7537
27	0.4837	0.3776	0.535	0.4654	-6.6435

From the Fig.5, the optimum combination of process parameters for multiple performance characteristics i.e., maximum material removal rate, minimum surface roughness and minimum dimensional deviation is pulse on time level 1, pulse off time level 2, servo voltage level1, water pressure level3, wire feed level3 and wire tension level 3. The estimated mean of the response characteristic can be determined by

$\mu_{grade=}$ $A_1+B_2+C_1+D_3+E_3+F_3-5T$

$=0.6372+0.5977+0.6123+0.5767+0.5780-5X0.569133 \quad =0.7537$

T is the average of grey relation grade corresponding to all the 27 readings

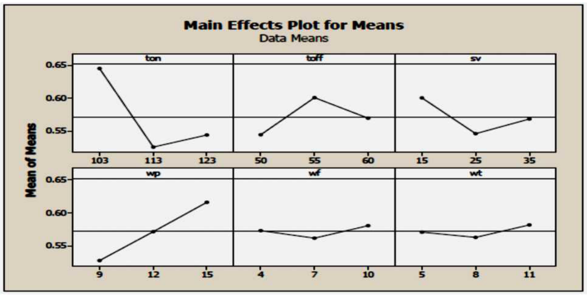

Fig.5.Effect of process parameters on Grey relation grade

Confirmation experiment was conducted at the optimum settings of process parameters. The output characteristics at this combination of input parameters are: MRR is 5.80mm^3/min, SR is1.82 µm and DD is0.465%.By using the procedure of grey relational analysis for the values mentioned above, the grey relational grade is 0.7587.The grade obtained with the experimental values poses less than 5% error with the predicted mean. The optimum conditions by using Taguchi optimization method and grey relational analysis is tabulated in the tables7 and 8

Table.7.Optimum conditions using Taguchi Optimization method.

Sl.No	Process parameter	Material Removal Rate, mm^3/min,		Surface Roughness, µm		Dimensional deviation, mm	
		Best level	Value	Best level	Value	Best level	Value
1	Pulse on Time, µs	3	1.25	1	0.25	1	0.25
2	Pulse off time, µs	1	26	3	46	3	46
3	Servo voltage, V	2	25	3	35	1	15
4	Di-electric pressure, Kg/cm^2	3	15	3	15	3	15
5	Wire feed ,m/min	3	10	1	4	1	4
6	Wire tension, N	3	15.68	1	5.88	3	15.68

Table.8.Optimum conditions using Grey Relational Analysis

Sl.No	Process Parameter	Best level	Value
1	Pulse on Time,µs	1	0.25
2	Pulse off time,µs	2	36
3	Servo voltage, V	1	25
4	Di-electric pressure, Kg/cm^2	3	15
5	Wire feed ,m/min	3	10
6	Wire tension, N	3	15.68

4. Conclusions

This paper has presented experimental studies on multi objective optimisation of process parameters on WEDM of AISI304 Stainless steel using Taguchi Grey Relational Analysis. The conclusions of this present study are

- The analysis of experimental results is carried out using Taguchi's orthogonal array and S/N ratio. The level of the best of the process parameters on machining of AISI304 Stainless steel and output parameters material removal rate , surface finish and dimensional deviationare determined by using S/N ratio.
- The optimum process parameters which provide maximum value of MRR are third level of pulse on time (A3), first level of pulse off time (B1), second level of servo voltage (C2), third level of water pressure (D3), third level of wire feed (E3) and third level of wire tension (F3).
- The optimum process parameters which minimum value of surface roughness arefirst level of pulse on time (A1), third level of pulse off time (B3), third level of servo voltage (C3), third level of water pressure (D3), first level of wire feed (E1) and first level of wire tension (F1).
- The optimum process parameters which provide minimum value of dimensional deviation are first level of pulse on time (A1), third level of pulse off time (B3), first level of servo voltage (C1), third level of water pressure (D1), first level of wire feed (E1) and third level of wire tension (F3)
- Optimum combination of process parameters for multiple performance characteristics using grey relational analysis is with pulse on time level1(A1), pulse off time level 2(B2), servo voltage level1 (C1), water pressure level3(D3), wire feed level3(E3) and wire tension level 3(F3).
- The grey relation grade obtained with the experimental values poses less than 5% error with the predicted mean.

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