

# Optimization and comparison of process parameters of die sinking electrical discharge machined stainless steel AISI 304, AISI 304L and AISI 304H

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## ABSTRACT

EDM (Electrical Discharge Machining) is a non-traditional thermo electrical machining process used for producing intricate and complex shapes or material parts that are extremely difficult-to-produce by usual traditional machining process. The principle of metal removal is by melting and vapourisation of metal which is possible by introducing many number of sparks between a tool electrode and a conductive work piece, in the presence of a dielectric fluid. The stainless steel is the highest produced and consumed material in the world. Especially AISI 304 stainless occupies approximately 50% of it. AISI 304 comes in three grades based on carbon content: 304, 304L & 304H. Its applications include architectural paneling and medical implants for 304, 304L is for chemical process equipment and equipment for food processing, 304H is for pressure vessels and equipment for petrochemicals. Previous research has been carried out with the goal of optimizing the process parameters of EDM for AISI 304 with Material Removal Rate (MRR) as the main focus. In this project, the relative suitability of each grade of 304 steel for EDM is determined by varying Gap current (I), Gap voltage (V) and pulse-on time (T) to get better surface roughness (Ra), high MRR and low Tool Wear Rate (TWR). The machining is carried out using Elektra Pride-Z and experiment is conducted using copper as electrode material and EDM oil as dielectric medium. The process is optimized using Central Composite Design (CCD). The model is validated by conducting experiments. From the experiments it is evident that the AISI 304 gives maximum MRR of 52.404mm<sup>3</sup>/min, AISI 304L gives the least TWR of 0.0035mm<sup>3</sup>/min and AISI 304H gives the least Ra value of 1.433 µm. Accordingly suggestions have been given to the industrial practitioners of EDM.

**KEY WORDS:** EDM, Optimization, AISI 304, 304L, 304H, MRR, TWR, surface roughness

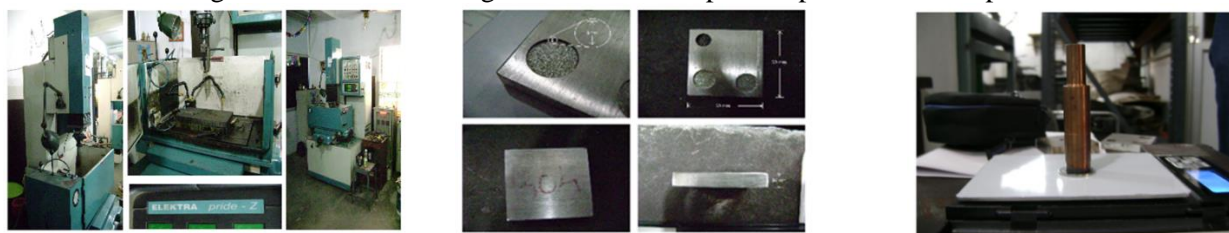
## 1. INTRODUCTION

Electrical discharge machining (EDM) process, is one of the most extensively used non-traditional machining processes. In EDM process the material is removed with the help of a pulsating DC generator which discharges the current between tool and work piece, termed as inter-electrode gap. The dielectric fluid fills the gap, which is responsible for ionisation thus producing electrical discharge between tool and work piece. Due to this a spark is generated, further which produces a tiny crater in the work piece by melting and vaporisation, and consequently tiny, spherical “chips” are produced by solidification of the melted quantity of work piece material. Bubbles are also produced from discharge gases. In this process even the tool is melted and vapourised at a minimal level compared to work piece due to the high temperature created by the spark between the tool and work piece. The flushing of chips and bubbles is carried out by the pumping action of new dielectric fluid into the inter-electrode gap while confining the sparks. Thus the process continues by producing another spark on the work piece in a different position. This phenomenon of producing thousands of sparks per second to remove material is described as spark erosion. Klocke (2013), studied the relation between the physical characteristics (Electrical resistance, thermal conductivity and grain size) of five grades of graphite electrode on one hand and the major EDM output parameters (MRR and TWR). Their research concludes that the discharge current is responsible for material removal rate and the discharge duration is responsible for tool wear. The tests revealed that main influence of the used material on the MRR originates from the electrical conductivity. The reason for wear of tool is still not obvious but seems to be a combination of the grain size, electric resistance and some of the material properties that are investigated. The deposition on the tool electrode are also explained using certain parameters. Hinduja (2013), reviewed several models and simulations namely to calculate the current density distribution in ECM, to measure plasma arc in EDM, to find out anodic dissolution in ECM and to determine the discharge location in EDM. Tiwari (2013), studied the various parameters affecting tool wear rate using copper as the tool electrode, mild steel as work piece and EDM oil as dielectric and optimized peak current, gap voltage and pulse on time for the process. Lin (2003), performed research on the effects of magnetic force on EDM machining characteristics. This work adopted an L<sub>18</sub> orthogonal array based on Taguchi method to conduct a series of experiments, and statistically evaluated the experimental data by analysis of variance (ANOVA). The main machining parameters such as machining polarity, peak current, pulse duration, high-voltage auxiliary current, no-load voltage and servo reference voltage were chosen to determine the EDM machining characteristics such as material removal rate (MRR) and surface roughness (SR). The experimental results show that the magnetic force assisted EDM has a higher MRR, a lower relative electrode wear ratio (REWR), and a smaller SR as compared with standard EDM. Ho (2003), reported on the EDM research relating to improving performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying

the electrode design and manufacture. A range of EDM applications are highlighted together with the development of hybrid machining processes. Fnides (2011), conducted an experimental study to determine statistical models of cutting forces in hard turning of AISI H11 hot work tool steel. The results indicate that the depth of cut is the dominant factor affecting cutting force components. The feed rate influences tangential cutting force more than radial and axial forces. The cutting speed affects radial force more than tangential and axial forces. Rahman (2011), investigated the effect of the peak current and pulse duration on the performance characteristics of the EDM of AISI 304 and concluded that at all values of pulse duration the material removal rate increases almost linearly with increases of discharge current. The combination of long pulse on time and high discharge current permits more material removal. Singh (2004), concluded that finest surface finish can be achieved by utilizing low peak ampere and long pulse on time combination. As peak current increases, the TWR increases and the impact of pulse on time on tool wear is contrary of peak current. From the literature review, we can conclude that a majority of research in EDM is focused on the optimization of the process with regard to MRR and TWR, while very few papers regard surface roughness as an important parameter. Research has been conducted on the EDM of AISI 304 but a comparative study of the three grades of AISI 304 (304, 304L, 304H) has not been performed. The aim of our project is to optimize and compare the process parameters of die sinking EDM for the three grades of AISI 304. The optimization is done using the Design of Experiments (DoE) approach of Response Surface Methodology (RSM).

## 2. EXPERIMENTAL DETAILS

The experiments are conducted using the die sinking type Electric Discharge Machine, model Electronica – Electra Pride-Z. The polarity of the electrode is set as positive while that of work piece as negative since less heat is generated so that better control is possible on erosion which leads to better surface finish and dimensional accuracy. The dielectric fluid used is EDM oil of specific gravity of 0.763. Three different grades AISI 304, AISI 304L and AISI 304H Stainless Steel are chosen as the work piece material as it is one of the most extensively used materials in different applications of industry and also world's stainless steel production and consumption is enormous. The work piece is of rectangular in cross section with dimensions 50 x 50 x 10 mm. The tool material is copper as it is the most commonly used material in EDM and the cross section of the tool is circular with dimension as 14.9mm diameter. The machining is done on all the materials to make a circular slot of 15mm diameter and thickness 1mm. The total machining time is 5mins/slot. Fig.1. shows the complete experimental set up.



**Figure.1. Experimental set up with machined work piece and tool**

The chemical composition of work piece material is given in Table.1. The literature survey yielded a range of parameter values in which the EDM of AISI 304 was deemed to be most effective

**Table.1. Chemical composition for AISI 304, AISI 304L and AISI 304H**

GRADE	C % (max)	Mn % (max)	P % (max)	S % (max)	Si % (max)	Cr %	Ni %
AISI 304	0.07	2	0.045	0.03	0.75	17.5-19.5	8.0-10.5
AISI 304L	0.03	2	0.045	0.03	0.75	17.5-19.5	8.0-10.5
AISI 304H	0.04-0.1	2	0.045	0.03	0.75	18-20	8.0-10.5

This along with the technical specifications of the EDM machine is being used, aided us in deciding the range of values of the controllable parameters in conducting the experiments. The values tabulated are shown in Table.2.

**Table.2. Machining Parameters and their levels**

Machining Parameter	Symbol	Unit	Levels				
			1	2	3	4	5
Current	I	A	2	5	9	13	15
Voltage	V	V	10	25	40	60	70
Pulse on time	T	Machine setting no.	17	29	49	63	79

As per the knob settings available in the machine the finalization of the range of parameter values have moved on to the most important steps in the entire process of forming of the Central Composite Design matrix. A Box-Wilson Central Composite Design, also named as 'a central composite design,' comprises an imbedded factorial or fractional factorial design with center points that is augmented with a group of 'star points'. If the distance from the center of the design space to a factorial point is  $\pm 1$  unit for each factor, the distance from the center of the design

space to a star point is  $\pm\alpha$  with  $|\alpha| > 1$ . The precise value of  $\alpha$  depends on certain properties desired for the design and on the number of factors involved. The value of  $\alpha$  is  $2^{n/4}$ , where  $n$  = number of factors,  $n=3$ ,  $\alpha = 1.682$ . Using the value of  $\alpha$  obtained, a CCD matrix for the experiments to be performed is generated which is shown in Table.3. Therefore 20 experiments are conducted for each grade of the work piece material. The MRR and TWR are calculated as follows.

**Table.3. CCD Matrix**

S.No.	Coded			Actual		
	I	V	T	I, A	V, V	T, setting no.
1	-1	-1	-1	5	25	29
2	1	-1	-1	13	25	29
3	-1	1	-1	5	60	29
4	1	1	-1	13	60	29
5	-1	-1	1	5	25	63
6	1	-1	1	13	25	63
7	-1	1	1	5	60	63
8	1	1	1	13	60	63
9	1.682	0	0	15	40	49
10	-1.682	0	0	2	40	49
11	0	1.682	0	9	70	49
12	0	-1.682	0	9	10	49
13	0	0	1.682	9	40	79
14	0	0	-1.682	9	40	17
15	0	0	0	9	40	49
16	0	0	0	9	40	49
17	0	0	0	9	40	49
18	0	0	0	9	40	49
19	0	0	0	9	40	49
20	0	0	0	9	40	49

MRR= (Weight of work piece before machining - Weight of work piece after machining) / (Machining time X Density of work piece material) (1)

TWR= (Weight of tool before machining - Weight of tool after machining) / (Machining time X Density of tool material) (2)

Density of work piece material, AISI 304 is 8073 Kg/m<sup>3</sup> and Density of tool material copper is 8960 Kg/m<sup>3</sup>. The weighing of the tool and the work piece is carried out using a Notebook series digital scale of resolution of 0.01 gm. The observed readings are carefully noted in tables as and when the experiments are performed. The surface roughness Ra is measured in microns using Surf coder SE1200. The experimental observations for all the grades of work pieces are calculated and tabulated in Table.4.

**Table.4. Results for AISI 304, AISI 304L and AISI 304H**

Current (A)	Voltage (V)	Pulse ON time (machine setting no.)	AISI 304		
			TWR (mm <sup>3</sup> /min)	MRR (mm <sup>3</sup> /min)	Ra (μm)
2	40	49	0.0037	0.517	2.81
5	25	29	0.2364	18.103	6.84
5	60	29	0.1282	8.891	6.13
5	25	63	0.3904	15.167	7.379
5	60	63	0.1537	7.961	7.165
9	70	49	0.0671	5.325	7.542
9	10	49	0.5016	21.292	7.742
9	40	79	0.2183	16.473	8.72
9	40	17	0.3412	15.526	4.764
9	40	49	0.1619	23.173	6.7
9	40	49	0.3352	24.928	7.867
9	40	49	0.1619	23.173	6.7
9	40	49	0.3352	24.928	7.867
9	40	49	0.1619	23.173	6.7
9	40	49	0.3352	24.928	7.867
13	25	29	1.1041	37.254	9.044

13	60	29	0.4037	19.862	9.981
13	25	63	0.5223	37.967	8.725
13	60	63	0.3666	19.258	11.305
15	40	49	0.3302	52.404	10.441

AISI 304L			AISI 304H		
TWR (mm <sup>3</sup> /min)	MRR(mm <sup>3</sup> /min)	Ra(μm)	TWR (mm <sup>3</sup> /min)	MRR(mm <sup>3</sup> /min)	Ra(μm)
0.0035	0.492	2.359	0.0073	0.479	1.433
0.3601	17.951	5.492	0.3559	16.707	6.11
0.1200	9.244	6.4	0.1153	8.934	7.14
0.3942	15.070	7.749	0.3048	15.193	5.843
0.0959	8.031	6.249	0.1509	7.305	5.642
0.0706	6.108	6.871	0.0662	5.161	9.098
0.2721	23.077	6.937	0.1399	22.132	6.102
0.2356	18.016	7.364	0.2323	17.621	6.148
0.5853	15.940	4.357	0.3457	15.855	5.246
0.1269	18.974	6.515	0.1282	18.469	8.363
0.1609	17.243	6.778	0.3396	24.286	8.276
0.1269	18.974	6.515	0.1282	18.469	8.363
0.1609	17.243	6.778	0.3396	24.286	8.276
0.1269	18.974	6.515	0.1282	18.469	8.363
0.1609	17.243	6.778	0.3396	24.286	8.276
0.4674	37.824	7.658	0.3620	34.120	8.658
0.1229	17.557	7.398	0.1298	18.144	5.963
0.5317	41.538	8.594	0.7954	37.054	9.503
0.7582	18.477	11.186	0.1292	18.196	9.361
0.3302	46.073	6.284	0.3347	48.592	8.166

### 3. RESULTS AND DISCUSSIONS

The linear regression analysis is been done for all the three grades of work pieces for all the process output responses like MRR, TWR and Ra for the input process parameters voltage, current and pulse on time.

**Analysis and Comparison of MRR between AISI 304, AISI 304L AND AISI 304H:** The regression equation for MRR are given by

For AISI 304

$$\text{MRR} = 23.925 + (2.214 * I) + (0.951 * V) + (0.535 * T) \quad (3)$$

For AISI 304L

$$\text{MRR} = 10.105 + (2.596 * I) - (0.353 * V) + (7.739\text{E-}003 * T) \quad (4)$$

For AISI 304H

$$\text{MRR} = 9.536 + (2.562 * I) - (0.327 * V) + (0.013 * T) \quad (5)$$

The correlation coefficients in the model are given by  $R^2=91.71\%$ ,  $R^2=83.02\%$  and  $R^2=79.95\%$  for AISI 304, AISI 304L and AISI 304H respectively. These values indicate that the model is capable of predicting the response with a high accuracy. The interaction plots are shown in Fig.2 which indicates that the MRR increases as the current increases throughout the entire range. The MRR decreases gradually along with the increase in voltage within the range. In case of AISI 304 considering pulse on time, the MRR first slightly increases up to setting number 49 and then decreases in a similar fashion till setting number 79. In case of AISI 304L and AISI 304H considering pulse on time, has a very less effect on MRR.

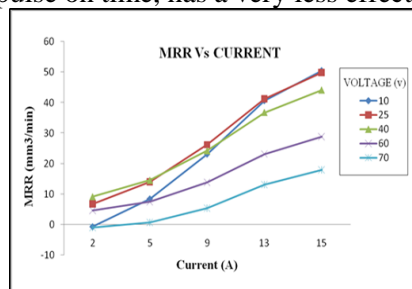


Figure.2 (a)

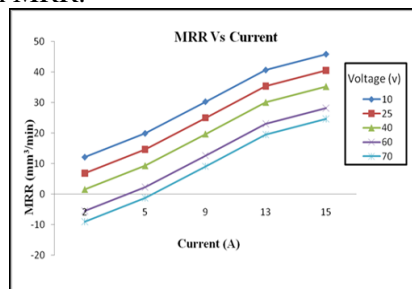


Figure.2 (b)

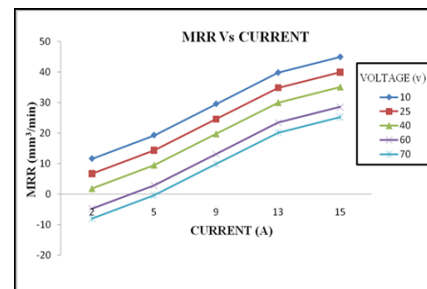


Figure.2 (c)

Figure.2. Interaction Plot – MRR vs Current keeping pulse on time at setting no.49 for (a) AISI 304, (b) AISI 304L and (c) AISI 304H

The MRR increases as current increases can be explained on the basis of increase in the rate of discharge energy which leads to faster melting and vaporization of metal due to high concentration of discharge energy in the spark gap, which makes the MRR value to higher level.

**Analysis and Comparison of TWR between AISI 304, AISI 304L AND AISI 304H:** The regression equation for TWR are given by

For AISI 304

$$TWR = 0.43 + (0.038 * I) - (7.522E-003 * V) - (3.234E-003 * T) \quad (6)$$

For AISI 304L

$$TWR = 2.445 - (0.109 * I) - (0.031 * V) - (0.051 * T) \quad (7)$$

For AISI 304H

$$TWR = 0.273 + (0.019 * I) - (5.573E-003 * V) + (5.015E-004 * T) \quad (8)$$

The correlation coefficients in the model are given by  $R^2 = 58.85\%$ ,  $R^2 = 68\%$  and  $R^2 = 83.46\%$  for AISI 304, AISI 304L and AISI 304H respectively. These values indicate that the model is able to predict the response with a high accuracy. The interaction plots are shown in Fig.3 indicate that the TWR increases as the current increases and decreases gradually along with the increase in voltage within the range. In case of AISI 304 considering pulse on time, TWR decreases with increase in pulse on time, which is true for AISI 304L and pulse on time is got a very less effect on TWR in the case of AISI 304H.

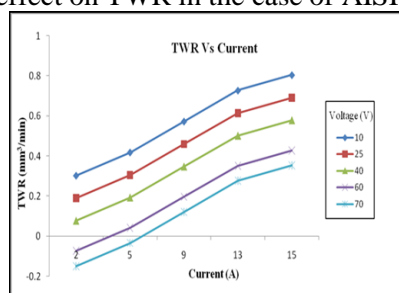


Figure.3 (a)

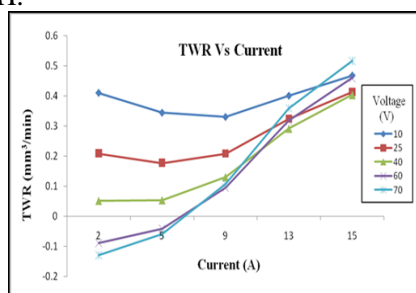


Figure.3 (b)

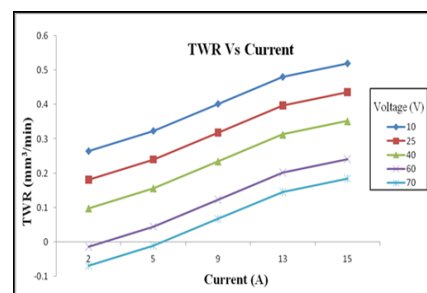


Figure.3 (c)

**Figure.3. Interaction Plot – TWRvs Current keeping pulse on time at setting no.49 for (a) AISI 304, (b) AISI 304L and (c) AISI 304H**

The increase in TWR with increase in current is explained as that whenever there is increase in discharge energy in the spark gap more heat is generated on both electrodes, thus erosion takes place TWR increases. It can be controlled by selecting proper dielectric medium, control parameters and polarity.

**Analysis and comparison of Ra between AISI 304, AISI 304L AND AISI 304H:** The regression equation for Ra are given by

For AISI 304

$$Ra = 1.327 + (0.454 * I) + (0.013 * V) + (0.035 * T) \quad (9)$$

For AISI 304L

$$Ra = 1.475 + (0.299 * I) + (0.012 * V) + (0.045 * T) \quad (10)$$

For AISI 304H

$$Ra = 2.186 + (1.209 * I) + (0.060 * V) + (0.072 * T) \quad (11)$$

The correlation coefficients in the model are given by  $R^2 = 72.84\%$ ,  $R^2 = 68\%$  and  $R^2 = 72.84\%$  for AISI 304, AISI 304L and AISI 304H respectively. These values indicate that the model is adequate of predicting the response with a high accuracy. The interaction plots are shown in Fig.4 indicate that the Ra value increases as the current and pulse on time increases within the range. Voltage has got a less effect on Ra value which is true for all the work piece materials.

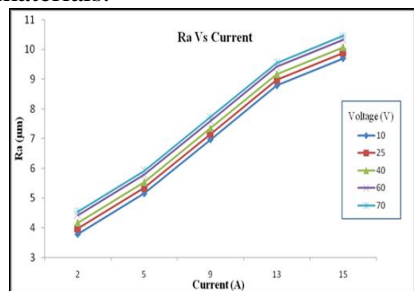


Figure.4 (a)

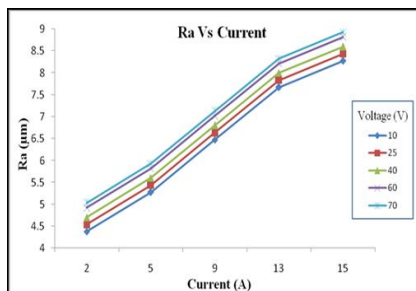


Figure.4 (b)

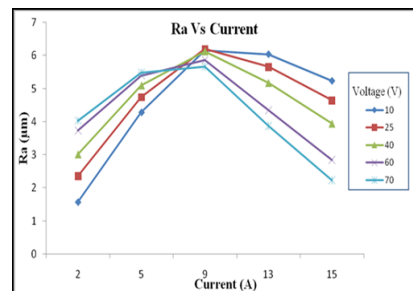


Figure.4 (c)

**Figure.4. Interaction Plot – Ravs Current keeping pulse on time at setting no.49 for (a) AISI 304, (b) AISI 304L and (c) AISI 304H**



The increase in surface roughness with increase in current can be explained as whenever there is increase in discharge energy more heat is generated towards work piece especially if it is given a positive polarity. This makes the process more erratic which leads to formation of recast layer thus increase in surface roughness.

**Process optimization of AISI 304, AISI304L AND AISI 304H:** The optimization was done using the Design Expert software. The conditions for optimization are maximum MRR, minimum TWR and minimum SR. The following are the input parameters obtained from the software model. The results are tabulated in Table.5. To validate the model experiments are done with the optimized input parameters. A comparison is done between experimental and theoretical responses, which are tabulated in Table.6, Table.7 and Table.8 for AISI 304, AISI 304L and AISI 304H respectively. It is concluded that the model is consistent with the experimentation with a minimal error.

**Table.5. Optimized input parameters**

Grade	Current (A)	Voltage (V)	Pulse on time (setting no.)
AISI 304	6.7	36.5	40
AISI 304L	9.4	21.2	47
AISI 304H	15	70	17

**Table.6. Comparison of experimental and theoretical responses–AISI 304**

Source	MRR (mm <sup>3</sup> /min)	TWR (mm <sup>3</sup> /min)	Ra (μm)
Theoretical value from model	18.899	0.287	6.263
Experimental result	10.529	0.074	6.01

**Table.7. Comparison of experimental and theoretical responses – AISI 304L**

Source	MRR (mm <sup>3</sup> /min)	TWR (mm <sup>3</sup> /min)	Ra (μm)
Theoretical value from model	27.31	0.270	6.625
Experimental result	18.83	0.125	6.35

**Table.8. Comparison of experimental and theoretical responses – AISI 304H**

Source	MRR (mm <sup>3</sup> /min)	TWR (mm <sup>3</sup> /min)	Ra (μm)
Theoretical value from model	25.34	0.185	2.24
Experimental result	18.56	0.156	2.34

#### 4. CONCLUSIONS

In this study the experiment was conducted by considering the parameters namely gap current, pulse on time and gap voltage of the process. The objective is to optimize the Material Removal Rate, Surface Roughness and Tool Wear Rate by varying the process parameters on these characteristics for each grade of AISI 304. The following conclusions were drawn:

- Considering the performance measures values obtained from the model for each grade of material and comparing it with the values obtained experimentally, AISI 304H material grade was found to be suitable for Electrical Discharge machining.
- During the experimentation stage, AISI 304 displayed the highest MRR value of 52.404mm<sup>3</sup>/min. AISI 304H had a maximum MRR of 48.592mm<sup>3</sup>/min and AISI 304L removed material at a maximum of 46.073 mm<sup>3</sup>/min.
- In the settings used for the 20 runs, AISI 304 displayed the maximum MRR in 55% of the instances followed by AISI 304L (40%) and AISI 304H (5%).
- AISI 304L has the least TWR of 0.0035mm<sup>3</sup>/min. AISI 304 has a minimum TWR of 0.0037 mm<sup>3</sup>/min while AISI 304H has a TWR of 0.0073mm<sup>3</sup>/min.
- AISI 304L has the least TWR in 50% of the runs, followed by AISI 304 H at 30% of the run and AISI 304 in 20%.
- In terms of surface roughness, the three grades can be ranked in the order of AISI 304H (1.433 μm), AISI 304L (2.359 μm) and AISI 304 (2.81 μm).
- Among the settings, AISI 304 L had the least SR in 55% of the runs. AISI 304H comes next (40%). AISI 304 has the least SR in only 5% of the runs.
- In the MRR interaction plots, the negative MRR values indicate that under those values of input parameters, material removal is not possible. Mostly low gap current and high voltage will result in negative MRR.
- In the TWR interaction plots, negative TWR is observed in some cases. One possible explanation for this would be the deposition of a significant quantity of work piece material on the tool.

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