Modeling and Optimization of Machining High Performance Nickel Based Super Alloy Nimonic C-263 Using Die Sinking EDM

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Abstract—**EDM is a renowned non-conventional machining process capable of producing precise tolerance on difficult to cut materials. However, machinability aspects of prodigious materials like Nimonic C-263 are yet to be explored. Thus, in the current study, various die sinking EDM process parameters are analyzed with reference to responses like material removal rate, tool wear rate, surface roughness and radial over cut on Nimonic C-263 super alloy. The machining parameters considered are Current (C), Pulse on-time (Ton), Pulse off-time (Toff) and Flushing Pressure (FP). The response variables observed are Material Removal rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Radial Overcut (ROC). TAGUCHI L25 orthogonal array is considered for experimental design and fine grained graphite as tool electrode during experimentation. Multiple regression analysis is performed on each response to develop mathematical model which are later used to predict the responses using optimal parameters. The results revealed, current as an influential process parameter affecting all the responses. The models are verified by validation experiments.**

Index Terms—**Electrical discharge machining, Nimonic C-263, metal removal rate, tool wear rate, surface roughness, radial over cut, Taguchi method and regression models**

I. Introduction

Super alloys are the materials that posses the best properties of contrary environments. Nickel based super alloys are one such material possessing superior strength and erosion resistance, even at elevated temperatures [1, 2]. Among different nickel based super alloys, Nimonic C-263 is an eminent aerospace high temperature alloy that exhibit high hot hardness and strength; in addition presence of austenitic matrix lead to poor machinability by conventional processes[3]. This necessitates the use of non-conventional machining techniques like EDM to finish-cut Nimonic C-263.

Materials like precipitation hardened aluminium embedded with ceramic reinforcements like SiC are successfully machined by Die sinking EDM technique [4, 5]. However, characteristics & topography of hard materials are severely affected by high temperature produced during thermal erosion mechanism [6]. Several electric parameters such as voltage, current, Pulse on-time, pulse off-time and non-electric parameters like flushing pressure, tool rotation and type of dielectric fluid are investigated [7-9]. Moreover, surface roughness, material removal rate and radial over cut are some of the response variables preferred during Die-sinking EDM process [10, 11]. Design of experiments is extensively used in investigation to emphasize the output responses in EDM [12, 13]. This summarizes that, majority of investigations are performed on modeling and optimization of output parameters obtained during EDM process. Die-sinking EDM is mostly used in machining ceramic–metal matrix composites while, a very few are interested in alloys like Titanium, Tool steel and Inconel.

Nimonic C-263 super alloy is gathering interest of researchers recently based on its potential applications .Therefore, this investigation is focused on modelling of Die-sinking EDM parameters that are affecting surface properties of Nimonic C-263 super alloy. The machining parameters considered are Current (C), Pulse on-time (Ton), Pulse off-time (Toff) and Flushing Pressure (FP). The response variables observed are Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Radial Overcut (ROC).Your goal is to simulate the usual appearance of papers in the. We are requesting that you follow these guidelines as closely as possible.

II. Experimental Details

A. Material and Equipment

The experiments are carried out on die-sinking EDM (CREATOR CR-6C) setup where commercially available EDM oil grade 2 is used as a dielectric fluid. Positive polarity is maintained throughout the experiment. The work piece used is Nimonic C-263 super alloy having a chemical composition as shown in Table I. The

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dimensions considered are flat plate of 30 mm X 15 mm with a thickness of 3 mm. Graphite has a very high vaporizing limit of 3500^0C that is capable of resisting high temperatures. While, materials capable to withstand high temperatures command lower wear rate and hence graphite is employed as the tool material in the current study. The tool dimensions are 12 mm diameter and 120 mm length procured from Nickunj Exmp. Pvt Ltd (Hyderabad). A total of 25 electrodes are used in the investigation.

B. Selection of Machining Parameters

The process parameters selected are based on the literature survey. The input variables selected are Peak Current (C), Pulse on-time (Ton), Pulse off-time (Toff) and Flushing Pressure (FP). Various levels considered in each process parameter are listed in Table II. The machining time was kept constant throughout the process. The output responses observed are Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Radial Overcut (ROC).

C. Design of Experiments

The experimental design of process parameters is performed using MINITAB software. TAGUCHI technique is employed to reduce the number of experiments from a full factorial design to an L-25 orthogonal array. A constant machining time of 5 minutes is considered for all experiments.

D. Measurement of Responses

MRR and TWR are determined by weight loss criteria by the help of digital weighing balance having an accuracy of 0.0001gms. The weight difference before and after the experimentation is calculated. SR is analyzed on texture of machined surface by Mitutoyo SJ-210. ROC is measured by using metallurgical microscope Leica DMi8.

TABLE I. CHEMICAL COMPOSITION OF NIMONIC C-263

Constituents	Ni	Cr	Co	Mo	Ti	C
Weight %	49.0	19.0-21.0	19.0-21.0	5.6-6.1	1.9-2.4	0.04-0.08

TABLE II. LEVELS CONSIDERED FOR L-25 ORTHOGONAL ARRAY

Process parameters	Current(C) in Amperes	Pulse-on-time(Ton) in µs	Pulse-off-time(Toff) in µs	Flushing Pressure(FP) in kg/cm^2
Level 1	4	18	12	0.2
Level 2	8	36	24	0.4
Level 3	12	54	36	0.6
Level 4	16	72	48	0.8
Level 5	20	90	64	1.0

III. PERFORMANCE EVALUATION

A. Material Removal Rate

In EDM process material erosion occurs due to local melting that is later flushed out by the dielectric fluid. It is impossible for dielectric fluid to flush out all the waste material which results in formation of re-cast or white layer that affects material characteristics. Fig.1 shows that, among various process parameters, current is the most prominent factor followed by pulse on time, while pulse off time has marginal affect on MRR. This phenomenon is strengthening by ANOVA results in Table III. illustrating a contribution of 72.84% by current followed by pulse on time 12.99%, on MRR. Mohanty *et al* [14] investigation on a different Ni-Cr alloy revealed that current and pulse on-time have nearly equal effect on MRR however, a marginal variation is noted for Ton in our investigation. This distinction is achieved by the graphite electrode material rather than copper in their research.

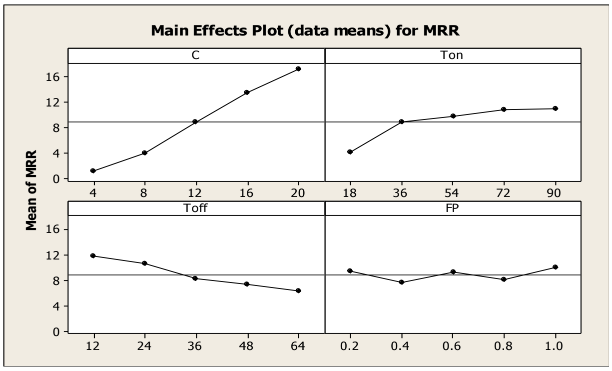


Figure 1. Main effects plot for MRR

TABLE III. ANOVA ANALYSIS FOR MRR

Source	DOF	SOS	MOS	F	P	% Cont.
Current	4	865.77	216.442	37.67	0	72.84
Pulse on-time	4	154.481	38.62	6.72	0.011	12.99
Pulse off-time	4	103.682	25.921	4.51	0.034	8.73
Flushing Pressure	4	18.84	4.71	0.82	0.547	1.58
Error	8	45.962	5.745			3.86
Total	24	1188.736				100

B. Tool Wear Rate

'Smaller the better' is the desired characteristic for tool wear rate to control the cost of machining. The mean effect plots of tool wear rate shown in Fig.2 depicts, a linear variation of TWR with increase in current and pulse on time but by a different factor. Pulse off-time and flushing pressure show a negligible effect on TWR. In addition, ANOVA of means for TWR as in Table IV. illustrates that current is highly influencing the TWR as indicated by percentage contribution of 92.12%, compared to other process parameters. A similar trend of increase in TWR with an increase in current is noted by investigators [15, 16]. Both these investigations used graphite electrode however, none of them used Nimonic super alloy.

During experimentation the TWR for all conditions is noted to be negligible inferring to high vaporizing point of graphite having no affect on wear. Moreover, some work piece material is observed to adhere to graphite electrode as a result TWR is noted to fluctuate between positive and negative values which is identical to the research made on Ni-Cr alloy using graphite electrode by Torres *et al*[17].

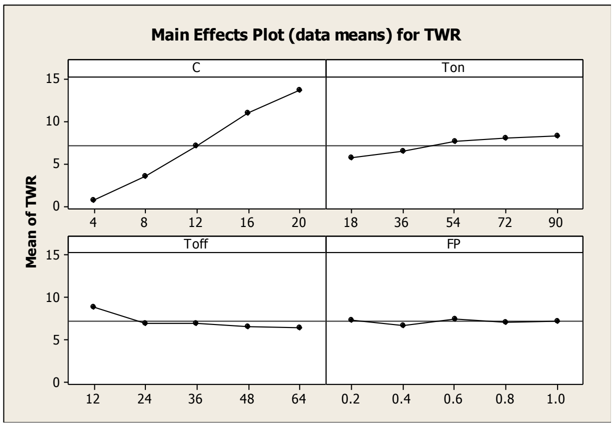


Figure 2. Main effects plot for TWR

TABLE IV. ANOVA ANALYSIS FOR TWR

Source	DOF	SOS	MOS	F	P	% Cont.
Current	4	567.212	141.803	271.22	0	92.12
Pulse on-time	4	23.393	5.848	11.19	0.002	3.80
Pulse off-time	4	19.234	4.809	9.2	0.004	3.12
Flushing Pressure	4	1.701	0.425	0.81	0.551	0.28
Error	8	4.183	0.523			0.68
Total	24	615.724				100

C. Surface Roughness

The variations in surface topography of a material lead to various unpredictable metallurgical anomalies during application. Therefore, surface roughness is a most desired factor during machining. From the plots of Fig.3 depicting the main effects of surface roughness, current and pulse on-time are noted to have identical and linear degree of variation. A contrary nature is observed for pulse off-time. Variation in flushing pressure seems to possess negligible change in surface roughness.

The analysis of variance details of our investigation (Table V) elucidates that pulse on-time is most influencing parameter followed by current and pulse off-time. This illustrates that; higher the pulse frequency (Ton) higher will be the rate of material splash getting solidified by dielectric fluid resulting in a bad surface topography. The percentage contribution of pulse on-time is 76.14% on surface roughness that is identical to Goswami *et al* [18]. According to Torres et al. [17], current intensity is the most influencing process parameter for surface roughness during the use of positive and negative polarities. While Goswami *et al* [18] revealed a contrary phenomenon of pulse on-time affecting the surface roughness. Both these studies only differ in use of discrete alloys of Ni-Cr i.e. Torres [17] used Inconel 600 while Goswami [18] worked on Nimonic 80A. However, contrary observations of current and pulse on-time as most influential parameters [17, 18] may be due to, Fe and Co that are the major ingredients next to Cr in Inconel 600 and Nimonic 80 A respectively. As Co is harder and poor conductor compared to Fe in Inconel 600, change in crater size and depth is expected to be marginal with an increase in current.

D. Radial over Cut

The radius of machined contour will always be greater than that of tool used and the difference of these parameters is termed as radial overcut. This parameter highly depends on the coefficient of thermal expansion of material considered for machining. At higher currents and voltages, the heat generated is also high leading to change in electrode tip dimensions for materials having high thermal expansion coefficient.

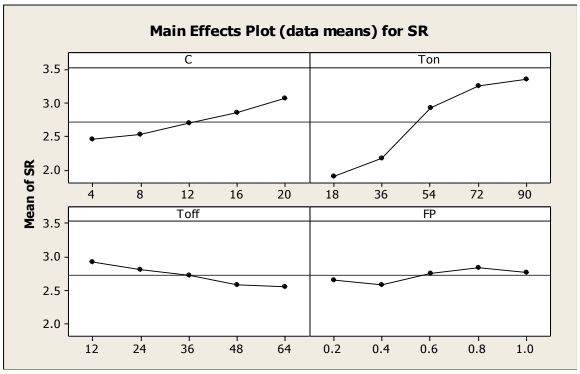


Figure 3. Main effects plot for SR

TABLE V. ANOVA ANALYSIS FOR SR

Source	DOF	SOS	MOS	F	P	% Cont.
Current	4	1.20631	0.30158	3.26	0.073	10.90
Pulse on-time	4	8.42615	2.10654	22.79	0	76.14
Pulse off-time	4	0.49335	0.12334	1.33	0.337	4.46
Flushing Pressure	4	0.20133	0.05033	0.54	0.708	1.82
Error	8	0.73937	0.09242			6.68
Total	24	11.06651				100

The main effecting process parameters for ROC obtained from generalized linear ANOVA analysis are as illustrated in Table VI. depicts the contribution of each process parameters on ROC. Current possessed 77.87% contribution in change of ROC followed by 7.20% for pulse on time. The mean effect plots of Radial overcut are shown in Fig.4 depicts, Current greatly influences the ROC, while pulse on-time is noted to show a marginal affect. Parameters like pulse off-time and flushing pressure show imperceptible response on ROC.

On correlating with the literature, pulse on time is the secondary parameter affecting ROC with a contribution of 15.49% during usage of copper electrode on Inconel 825 [14], however work performed on this radial overcut is scarce. The distinction observed between the articles is due to use of graphite having low thermal expansion and hence the electrode tip is stable even at high temperatures [15].

The Fig.5 illustrates various phenomenon considered for response variables; MRR uses “Larger is better” while the rest of the responses use “Smaller is better” characteristics. Fig. 5(a) depicts the effect of different process parameters on MRR. It also signifies the optimal conditions for the design as C-20, Ton-90, Toff-12 and FP-0.2. While, ideal conditions for TWR are obtained from Fig. 5(b) are C-4, Ton-36, Toff-64 and FP-1.0. In a similar procedure the optimal conditions for SR (C-4, Ton-18, Toff-64 and FP-0.4) and ROC (C- 4, Ton-36, Toff-64 and FP-0.6).

The optimum conditions for various responses are observed to lie outside the L-25 orthogonal array which necessitates the need for validation experiments. Therefore, validation runs are performed for the optimal conditions and are listed in Table VII. for comparison with predicted optimum response values. The predicted values for optimal conditions are attained from *Eq.1-4* (MRR, TWR, SR and ROC respectively) obtained from regression analysis conducted for experimental values. The average error obtained between the predicted and experimental runs is 5.07% i.e. the accuracy of the developed models is as high as 94.93%.

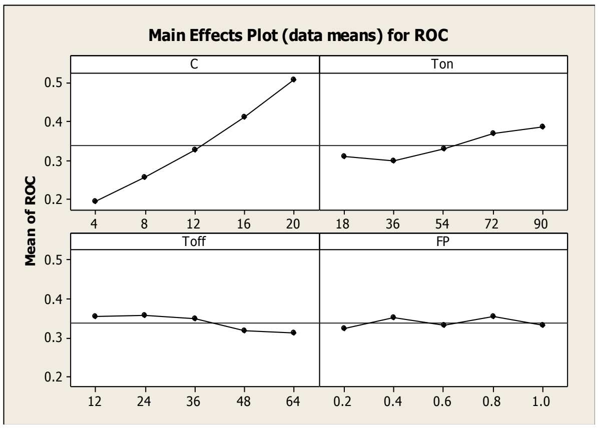
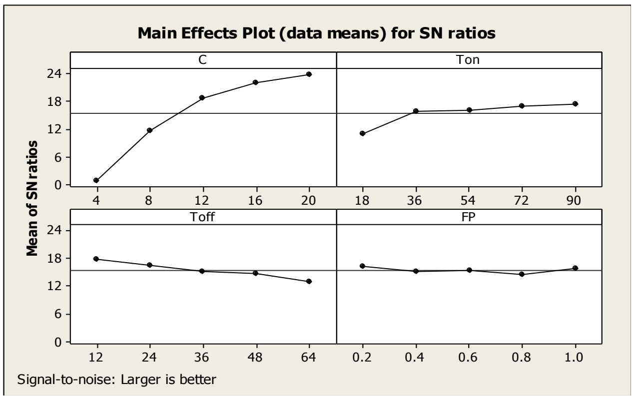


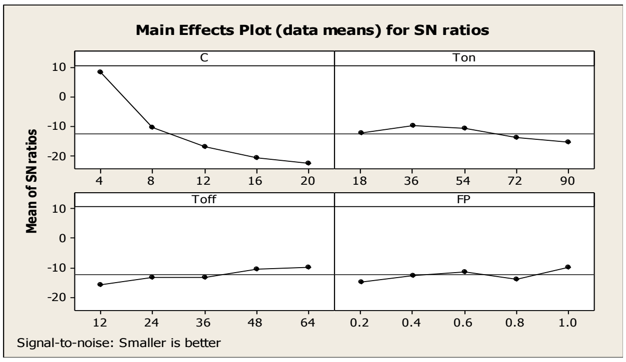
Figure 4. Main effects plot for ROC

TABLE VI. ANOVA ANALYSIS FOR ROC

Source	DOF	SOS	MOS	F	P	% Cont.
Current	4	0.305790	0.076448	13.39	0.001	77.87
Pulse on-time	4	0.028253	0.007063	1.24	0.368	7.20
Pulse off-time	4	0.009220	0.002305	0.40	0.801	2.35
Flushing Pressure	4	0.003789	0.000946	0.17	0.950	0.96
Error	8	0.045668	0.005708			11.62
Total	24	0.392715				100



5(a)



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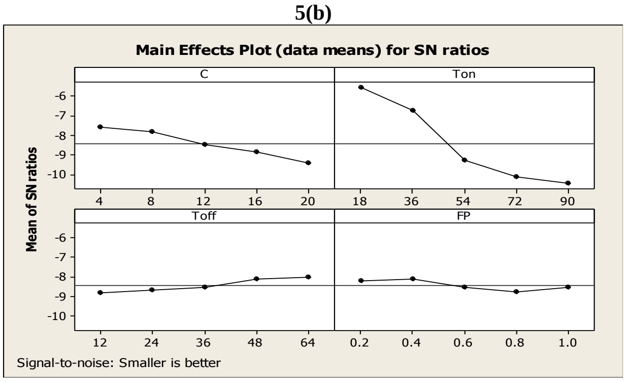

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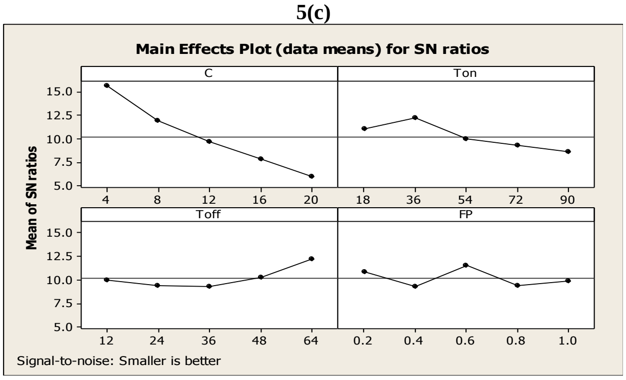

5(d)

Figure 5. Signal to Noise ratio plot for (a) MRR, (b) TWR, (c) SR and (d) ROC

$$MRR = - 6.50 + 0.252\ C + 0.000\ Ton + 0.331\ Toff + 14.6\ FP - 0.00075\ C*C - 0.00332\ Ton*Ton - 0.00444\ Toff*Toff - 11.8\ FP*FP + 0.0135\ C*Ton - 0.00038\ C*Toff + 0.105\ C*FP + 0.00317\ Ton*Toff + 0.239\ Ton*FP - 0.332\ Toff*FP \quad (1)$$

$$TWR = - 4.76 + 0.871\ C - 0.069\ Ton + 0.101 Toff + 9.6\ FP + 0.00125\ C*C - 0.00139\ Ton*Ton - 0.00087\ Toff*Toff - 8.1\ FP*FP - 0.00065\ C*Ton - 0.00330\ C*Toff + 0.154\ C*FP + 0.00324\ Ton*Toff + 0.200\ Ton*FP - 0.300\ Toff*FP \quad (2)$$

$$SR = 1.45 + 0.088\ C + 0.0874 Ton - 0.0796 Toff - 4.96\ FP + 0.000907\ C*C + 0.000367\ Ton*Ton + 0.000957\ Toff*Toff + 3.97\ FP*FP - 0.000226\ C*Ton - 0.00078\ C*Toff - 0.0429\ C*FP - 0.00135\ Ton*Toff - 0.0768\ Ton*FP + 0.117\ Toff*FP \quad (3)$$

$$ROC = - 0.209 - 0.0129 C - 0.0073 Ton + 0.0200 Toff + 1.70 FP + 0.000172 C*C - 0.000153 Ton*Ton - 0.000267 Toff*Toff - 1.11 FP*FP + 0.000191 C*Ton + 0.000534 C*Toff - 0.00614 C *FP + 0.000263 Ton*Toff + 0.0195 Ton*FP - 0.0304 Toff*FP \quad (4)$$

Surface cracks produced during machining severely hammer the strength of the component as they penetrate into interface with dissimilar contraction of resolidified structures. Micrographical investigations performed on EDM machined surfaces revealed a phenomenon of increase in micro-sized crack density with an increase in peak current [6]. Hence in our investigation sample surfaces machined at highest peak current are explicitly monitored for micro cracks. The Fig. 6 illustrates the absence of micro cracks resulting in stronger machined components of Nimonic C-263.

TABLE VII. VALIDATION OF PERFORMANCE RESULTS

Parameter	Optimum condition	Predicted optimum value	Experimental values
MRR	Current-20 T on-90 T off- 12 Flushing pressure-0.2	9.07	9.32
TWR	Current-4 T on-36 T off- 64 Flushing pressure-1.0	-2.34	-2.39
SR	Current-4 T on-18 T off- 64 Flushing pressure-0.4	1.58	1.51
ROC	Current-4 T on-36 T off- 64 Flushing pressure-0.6	0.09	0.08

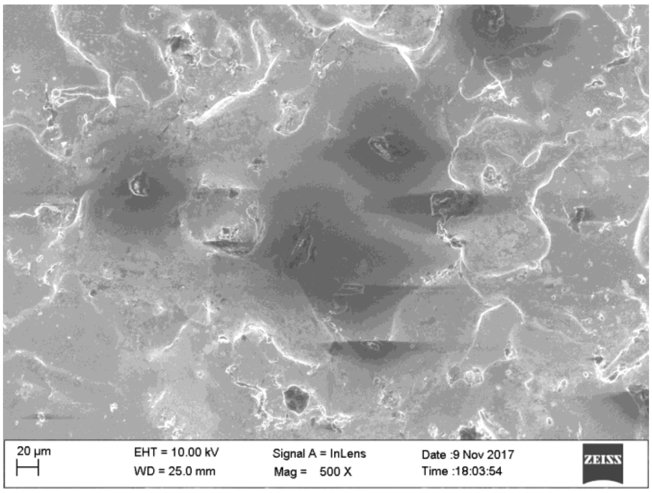

Figure 6. SEM image for (C-20, Ton-90, Toff-12 and FP-1) sample

IV. CONCLUSIONS

The present study exploits the influence of various Die sinking EDM process parameters on machinability of Nimonic C-263 super alloy by Taguchi technique. The following attributes are summarized

- At optimal condition, MRR increases with increase of Current & Pulse-on-time, while MRR is noted to be inversely proportional to Pulse-off-time. As flushing pressure increases MRR decreases up to 0.4 flushing pressure and then increases.
- The TWR at optimal condition increases with increase of Current & Pulse-on-time. While, a contrary result is seen for Pulse-off-time. Flushing pressure has negligible significance on TWR.
- Increase in Current and Pulse-on-time, increases the Surface Roughness at optimal condition. While, increase in pulse-off-time leads to decrease in surface roughness. Flushing pressure is observed to nominally affect the Surface Roughness.
- The Radial Over cut at ideal condition varies significantly with current and marginally by Pulse-on-time, due to thermal stability of graphite electrode. A contrary trend is observed for Pulse-off-time and a negligible influence is found for flushing pressure.
- All responses are greatly influenced by Current while Surface Roughness is significantly influenced by Pulse-on-time followed by Current.
- Flushing pressure followed by Pulse-off-time has nominal influence on output responses.
- Validation Experiments performed for optimal conditions showed improvement in different output responses compared to initial experimentation run.

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