ISSN No.: 2455-6130
Volume 1, Issue 11, 2016, pp. 06-15

website: www.ijoetr.com

International Journal of Emerging Trends in Research

Predicted Cutting Speed Modeling of Process parameters of WEDM for Inconel X 750

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Abstract

Non conventional machining processes, wire electro discharge machining (WEDM) plays important role in precision manufacturing. In wire EDM it is very difficult to choose correct combination of machining parameters and material for various responses like surface cutting speed etc. Obtaining better CS for Inconel-750 by conventional machining is a difficult task. In this paper effect of WEDM parameters on Inconel 750 are investigated. The Response surface methodology (RSM) was chosen for designing and conducting the experiments. The Analysis of variance (ANOVA) was done to determine the optimum machining parameter combination for CS. The regression analysis method was used to formulate the mathematical model. The experimental result shows that the predicted model suggested by the RSM method is suitable for improving the CS.

Keywords: ANOVA; WEDM; CCD, machining

1. Introduction

The machining of super alloys is an active research area because of the widespread increase in demand of this category of materials and characteristic problems related to their machining. Inconel 750 is a high-strength temperature- resistant (HSTR) nickel-based super alloy which exhibits good resistance to corrosion and oxidation along with high creep-rupture strength and fatigue endurance limit. It is extensively used in the aerospace industry for manufacturing of gas turbine engine components such as turbine disks, blades, combustors and casings, nuclear power plant components such as reactor and pump, spacecraft structural components, medical devices, food processing equipment, extrusion dies and containers, casting dies, hot work tools and dies, etc.. Machining of Inconel 750 with conventional techniques is extremely difficult because of its high toughness, hardness, work hardening tendency, low thermal conductivity, and presence of hard abrasive particles. Therefore, nonconventional machining methods based on chemical, electro-chemical, thermal, thermoelectric, and mechanical energy are preferred over traditional methods for the machining of Inconel 750. Wire electrical discharge machining (WEDM) is a non-conventional, thermoelectric process that can be used to cut complex and intricate shapes in all electrically conductive materials used in tool and die, automobile, aerospace, dental, nuclear, computer, and electronic industries with better precision and accuracy. WEDM is a well-established process and its working is duly described in the literature. The most important performance measures in WEDM are material removal rate (or cutting speed), surface finish, kerf (cutting width), and wire wear rate. These measures, in turn, are influenced by numerous machining parameters such as peak current, pulse-on time, pulse-off time, wire tension, wire feed rate, spark gap voltage, and servo feed setting, average working voltage, and dielectric flushing condition. Owing to a large number of process parameters and a complex nature of the process, even a highly skilled operator with a state-of-the-art WEDM is rarely able to achieve the optimal performance. The improperly selected parameters may also result in serious consequences like short-circuiting of wire and wire breakage that in turn reduces productivity. An effective way to solve this problem is to determine the relationship between the performance measures and the controllable input parameters using a suitable modelling and optimization technique.

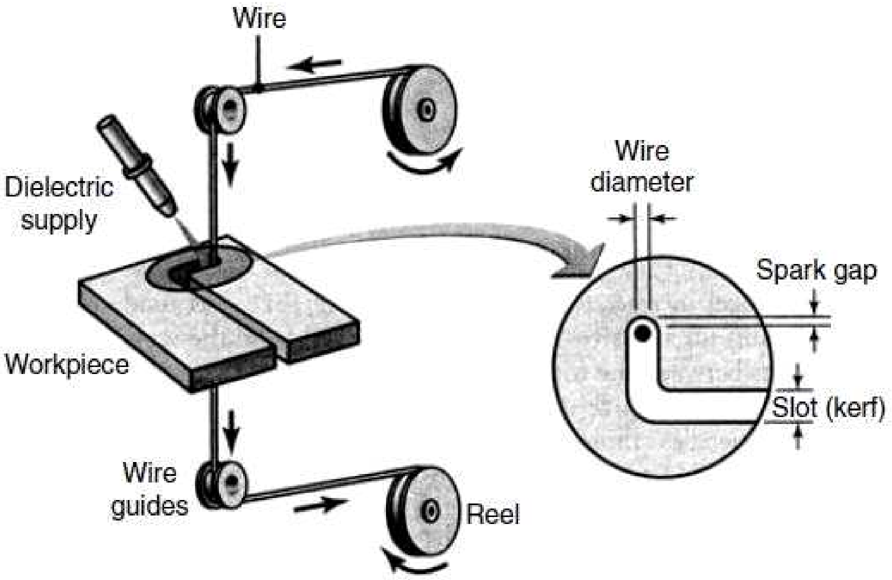

Figure 1: Schematic diagram of WEDM

2. Literature Review

Duniraj et al. (2013) described the optimization of process parameters in Wire EDM with stainless steel using single objective Taguchi method and multi objective grey relation grade. For experimentation Taguchi s LI6 orthogonal array has been used. They investigated that the effect of input parameters such as gap voltage, wire feed, pulse-on-time and pulse-off-time on the surface roughness and kerf width. By using multi-objective optimization technique grey relational theory, the optimal input parametric combination has been found as 50V gap voltage, 2mm/min wire feed, 4 μs pulse on time and 4 μs pulse off time. The analysis of variance resulted that the pulse-on-time has major influence in the surface roughness and kerf width,

Hevidy et al. (2005) modeled the machining parameters of wire electrical discharge mining of Inconel 601 using RSM. They investigated the effect of input parameters such as peak current, duty factor, wire tension and water pressure on the metal removal rate, wear ratio and surface roughness. They concluded that the volumetric metal removal rate generally increase with increase of peak current value and water pressure This trend has been valid up to the generation of arcing, after certain limit, the increase of peak current leads to the decrease of MRR and concluded that the wear ratio increase with the increase if peak current and decrease with the increase of duty factor and wire tension. The best surface finish (Ra) that has been reached is 0.8 micron meter. Wire tension and wire speed were changed to explore their effect on machining performance, including the cutting speed, the width oil slit and surface roughness, Moreover, the wire electrode was easily broken during the machining A12O3p/606 I AI composite, so that work comprehensively investigated into the location of broken wire and the reason of wire breaking They concluded that the machining of A12O3p/6061Al composite a very low wire tension. a high flushing rate and a high wire speed were required to prevent wire breakage with an appropriate servo voltage, a short pulse-on- time and a short pulse-off-time.

Kanlayasiri and Boonmung (2007) investigated influence of wire-EDM machining variables on surface roughness of newly developed DC53 die steel of width, length, and thickness 27, 65 and 13 mm, respectively. The machining variables included pulse on time, pulse off time, peak current and wire tension. The variables affecting the surface roughness were identified using ANOVA technique. Result showed that the pulse on time and peak current were significant variables to the surface roughness of wire-EDM DC53 die steel. The maximum prediction error of the model was less than 7% and average percentage error of prediction was less than 3%.

Kanlayasiri and Boonmung (2007) investigated the effects of wire EDM machining parameters on surface roughness of DC53 die steel. The investigated machining parameters were pulse-on time. pulse-off time, pulse-peak current and wire tension Analysis of variance (ANOVA) technique was used to find out the parameters affecting the surface roughness. Assumptions of ANOVA were examined through residual analysis. Quantitative testing methods on residual analysis were employed in place of the typical qualitative testing techniques. Results from ANOVA showed that pulse-on time and pulse peak current are significant variables for surface roughness. The surface roughness of test specimen increased as these two variables increased

Mgoudar and Sadashivappa (2013 investigated the effect of machining parameters on no and surface roughness in machining of ZA43/SiCp composite by WEDM. They investigated that the effect of input parameters likes' current, pulse-on-time, pulse-off-time on be MMR and surface roughness. They observed a reduction in the MMR and increase in surface roughness for increased reinforcement in the composite they also observed that increment in applied current and pulse-on-time increases the MMR

Pudand Bhattacharyya (2005) an attempt has been made to model the white layer dept through response surface methodology (RSM) in WEDM process comprising a rod cut followed by a trim cut. An experimental plan of rotatable central composite desk considering of four input variables, such as the pulse off-time during rough cutting (RT on) and pulse-on-time (TT on), offset and cutting speed during cutting have been modesty. It was concluded that the white layer depth increased with increased pulse-on- structuring the first rough cut and subsequently decreased while increasing pulse-on- time during trim cutting. The white layer depth reduce with decreasing wire tool off-set during trim cutting

Satishkumar et al. (2011) reported the investigation of the machining characteristics of AI6063/SiCp composites material in WEDM. in this investigation, the effect of wire electrical discharge machining (WEDM) parameters such as pulse-on time (Ton), pulse-off time (Toff), gap voltage (V) and wire feed (F) on material removal rate (MRR) and surface roughness (Ra) was studied. The AI6063 is reinforced with SiCp in the form of particles with 5%, 10% and 15% volume fractions. The experiments are carried out as per design of experiments approach using L9 orthogonal array. The results were analyzed using analysis of variance and response graphs. The results were also compared with the results obtained for unreinforced A16063. Generally, it was found that the increase in volume percentage of SiC resulted in decreased MRR and increased Roughness. Regression equations have been developed based on the experimental data for the prediction of output parameters for AI6063 and composites.

Shayan et al. (2013) described the parametric study along with selection of optimal solution in dry wire cut machining of cemented tungsten carbide (WC-Co), Experiments have been conducted using air as dielectric medium to investigate effect of pulse-on-time, pulse-off-time, gap set voltage, discharge current and wire tension on cutting velocity, surface roughness and oversize, A central composite rotatable method was employed to design experiments based on response surface methodology (RSM), Empirical model were developed to create relationship between process factors and response by considering to analysis of variance (ANOVA). These models were associated with optimization approaches namely desirability function and PSO. Result indicated that selection of air at inlet pressure of 1.5 bar leads to higher MRR and lower surface roughness. They concluded that the cutting velocity and surface roughness increase by increasing the discharge current and pulse-on-time. But increased pulse-on-time leads to lower oversize. Based on the results of the preliminary experiments, Cutting velocity and sure roughness were found to be decreased by increasing pulse-off-time and gap set voltage.

3. Experimental procedure

In present work, a 5 axis sprint cut WEDM is used for conducting the experiments, made by Electronica M/C Tool LTD, india. The performance of WEDM depends on setting of process parameters. Following section discusses the work material, machining parameters and experimental design used for present study.

3.1 Work material

Inconel is a family of austenitic nickel-chromium-based super alloys. The name is a trademark of Special Metals Corporation. There are different types of *Inconel alloys*. Different Inconels have widely varying compositions, but all are predominantly nickel, with chromium as the second element. The different Inconel alloys are 600, 617, 625, 718, and X750. The composition of Inconel X750 is as follows:

Table 1. Composition of *Inconel X750*

Component	**Wt. %**	**Component**	**Wt. %**	**Component**	**Wt. %**
Al	0.4 - 1	Cu	Max 0.5	Ni	Min 70
C	Max 0.08	Fe	5 - 9	S	Max 0.01
Co	Max 1	Mn	Max 1	Si	Max 0.5
Cr	14 - 17	Nb	0.7 - 1.2	Ti	2.25 - 2.75

3.2 Machining parameters

Four discharge parameters, viz. Ip, Ton, Toff and SV are selected as input variable parameters other remaining least significant parameters are kept constant. A brass wire (zinc coated) of diameter 0.25 mm is selected as wire electrode. Wire feed rate 5 m/min is used with wire tension 10N. All experiments are performed at zero wire offset value. The distilled water having conductivity, 20mho is used as a dielectric fluid with high flow rate (i.e. 12 L/min). Selected levels and range of four variable input parameters are shown in Table 1 series of experimental trials have been conducted as per response surface methodology (RSM). The details about the work material, experimental set-up and measuring apparatus, selection of process parameters and their range, design of experiments, and reproducibility have been explained in the following sections.

3.3 Selection of process parameters and their range

In the present work, the effect of various process parameters (factors) such as viz., Ip, Ton, Toff and SV on cutting speed (response parameters) has been investigated. These process parameters and their range have been selected on the basis of the existing literature, pilot experimentation, manufacturer's manual, and machine capability. The independent process parameters and their levels in coded and actual values are shown in Table 2.

3.4 Response Surface Methodology

Response surface methodology (RSM)[1] is a collection of mathematical and statistical techniques useful for analyzing problems in which several independent variables influence a dependent variable or response, and the goal is to optimize this response (Cochran and Cox, 1962). In many experimental conditions, it is possible to represent independent factors in quantitative form as given in Equation 3.1. Then these factors can be thought of as having a functional relationship with response as follows:

$$Y=\phi(X_1, X_2 \ldots\ldots\ldots\ldots\ldots, X_k)\pm e_r \qquad (3.1)$$

This represents the relation between response Y and $x1, x2, \ldots, xk\ of\ k$ quantitative factors. The function ϕ is called response surface or response function. The residual er measures the experimental errors (Cochran and Cox, 1962). For a given set of independent variables, a characteristic surface is responded. When the mathematical form of ϕ is not known, it can be approximated satisfactorily within the experimental region by a polynomial. Higher the degree of polynomial, better is the correlation but at the same time costs of experimentation become higher.

For the present work, RSM has been applied for developing the mathematical models in the form of multiple regression equations for the quality characteristic of machined parts produced by turning process. In applying the response surface methodology, the dependent variable is viewed as a surface to which a mathematical model is fitted. For the development of regression equations related to various quality characteristics of turning process, the second order response surface has been assumed as:

$$y = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_i x_i^2 + \sum_{i<j=2}^{2} b_i x_i\, x_j \pm e_r \qquad (3.2)$$

This assumed surface Y contains linear, squared and cross product terms of variablesxi"s. In order to estimate the regression coefficients, a number of experimental design techniques are available. Box and Hunter (1957) have proposed that the scheme based on central composite rotatable design fits the second order response surfaces quite accurately.

3.4.1 Central composite design

Box and Hunter [38] proposed that the scheme based on central composite design (CCD) fits the second-order re- sponse surfaces quite accurately. Also, CCD[1] is the most popular among the various classes of RSM designs due to its flexibility, ability to run sequentially, and efficiency in providing the overall experimental error in a minimum number of runs. Therefore, it has been selected in the present work. In CCD, each factor is varied at five levels (−α, −1, 0, 1, α) for developing a second-order model as given in Eq. (2). When the number of factors (k)isfive or greater, it is not necessary to run all combinations of factors. The factorial part of the design can be run using a fraction of the total number of available combinations. The possible designs options can either be regular fractional factorials.

4. Results and discussion

The present chapter gives the application of the response surface methodology. The scheme of carrying out experiments was selected and the experiments were conducted to investigate the effect of process parameters on the output parameter e.g. cutting speed. The experimental results are discussed subsequently in the following sections. The selected process variables were varied up to four levels and central composite rotatable design was adopted to design the experiments. Response Surface Methodology was used to develop second order regression equation relating response characteristics and process variables. The process variables and their ranges are given in Table 2.

Table 2: Process parameters and their levels

Coded	**Real**	**Parameters**	**Levels**		
Factors	**Factors**		**(-1)**	**(0)**	**(+1)**
A	Ton	Pulse on Time	105	112	130
B	Toff	Pulse off Time	35	40	45
C	SV	Spark Gap Set Voltage	30	38	45
D	IP	Peak Current	105	190	120

4.1 Experimental Results

The WEDM experiments were conducted, with the process parameter levels set as given in Table 2, to study the effect of process parameters over the output parameters. Experiments were conducted according to the test conditions specified by the second order central composite design (Table 2). Experimental results are given in Table 3 for cutting speed. Altogether 20 experiments were conducted using response surface methodology.

Table 3: Observed Values for Performance Characteristics

		Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response 1**
Std	Run	A:Peak current	B:Pulse on time	C:Pulse off time	D:Servo voltage	Cutting speed
12	1	112	130	40	37	2.71
10	2	120	117	40	37	2.385

11	3	112	105	40	37	1.45
15	4	112	117	40	30	2.53
3	5	120	105	45	45	0.916
17	6	112	117	40	37	2.38
7	7	105	130	45	45	2.168
2	8	120	130	35	30	2.892
14	9	112	117	45	37	2.145
19	10	112	117	40	37	2.38
21	11	112	117	40	37	2.6
8	12	105	105	35	30	1.464
16	13	112	117	40	45	2.23
4	14	105	130	35	45	2.356
18	15	112	117	40	37	2.38
6	16	105	105	45	30	1.052
13	17	112	117	35	37	2.445
5	18	120	105	35	45	1.4
1	19	120	130	45	30	2.704
9	20	105	117	40	37	2.185
20	21	112	117	40	37	2.38

4.2 Analysis and Discussion of Results

The experiments were designed and conducted by employing response surface methodology (RSM). The selection of appropriate model and the development of response surface models have been carried out by using statistical software, "Design Expert (DX-9)".

The regression equations for the selected model were obtained for the response characteristics viz. cutting speed. These regression equations were developed using the experimental data (Table 4.3) and were plotted to investigate the effect of process variables on various response characteristics. The analysis of variance (ANOVA) was performed to statistically analyze the results.

4.3.1 Selection of Adequate Model

To decide about the adequacy of the model, three different tests viz. sequential model sum of squares, lack of fit tests and model summary statistics were performed for cutting speed characteristic of WEDM process. The sequential model sum of squares test in each table shows how the terms of increasing complexity contribute to the model. It can be observed that for all the responses, the quadratic model is appropriate. The „lack of fit‟ test compares the residual error to the pure error from the replicated design points. The results indicate that the quadratic model in all the characteristics does not show significant lack of fit, hence the adequacy of quadratic model is confirmed. Another test „model summary statistics‟ given in the following sections further confirms that the quadratic model is the best to fit as it exhibits low standard deviation, high "R-Squared" values, and a low "PRESS"

4.3.2 Effect of Process Variables on Cutting Speed

The regression coefficient of the second order equation is obtained by using the experimental data (Table 2). The regression equation for the cutting speed as a function of five input process variables was developed using experimental data and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

$$\begin{aligned} Cutting\ Speed = {} & 59.30671 + 0.47442 * Peakcurrent + 0.49211 * Pulseontime + 0.18246 \\ & * Pulseofftime - 0.020960 * Servovoltage + 1.04000E - 003 * Pulseontime \\ & * Pulseofftime - 2.04502E - 003 * Peakcurrent^2 - 2.04821E - 003 \\ & * Pulseontime^2 - 4.20130E - 003 * Pulseofftime^2 \end{aligned} \tag{4.1}$$

The above response surface is plotted to study the effect of process variables on the cutting speed and is shown in Figures 4.1a-4.1b. From Figure 4.1a the cutting speed is found to have an increasing trend with the increase of pulse on time anddecrease the peak current peak current. This

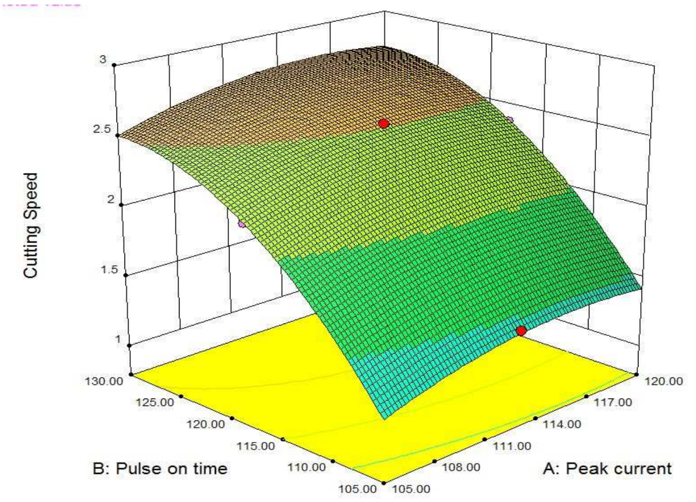

Figure 4.1a: Combined Effect Of Pulse on Time And Peak Current On Cutting speed

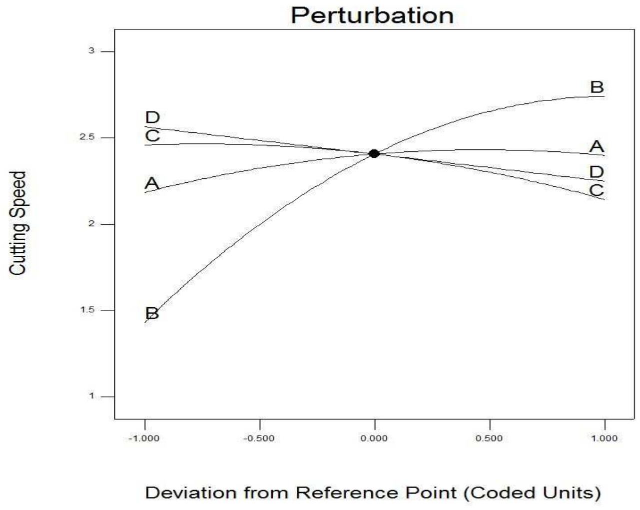

Figure 4.1b: Overall performance of Cutting speed

establishes the fact that cutting speed is proportional to the energy consumed during machining and is dependent not only on the energy contained in a pulse determining the crater size, but also on the applied energy rate or power. It is observed from Figure 4.1b that cutting speed decreases with increase servo voltage. With increase in spark voltage the average discharge gap gets widened resulting into a lower cutting speed. It is seen from Figure 4.1b that cutting speed increases with increase in the peak current values. The higher is the peak current setting, the larger is the discharge energy. This leads to increase in cutting speed. But, the sensitivity of the peak current setting on the cutting performance is stronger than that of the pulse on time. While the peak current setting is too high, wire breakage may occur frequently. It is seen from Figure 4.1d that cutting speed almost remains constant with increase in the peak current. Though with increase in peak current, the machining stability increases as vibrations get restricted. But its increment does not influence the cutting speed much.

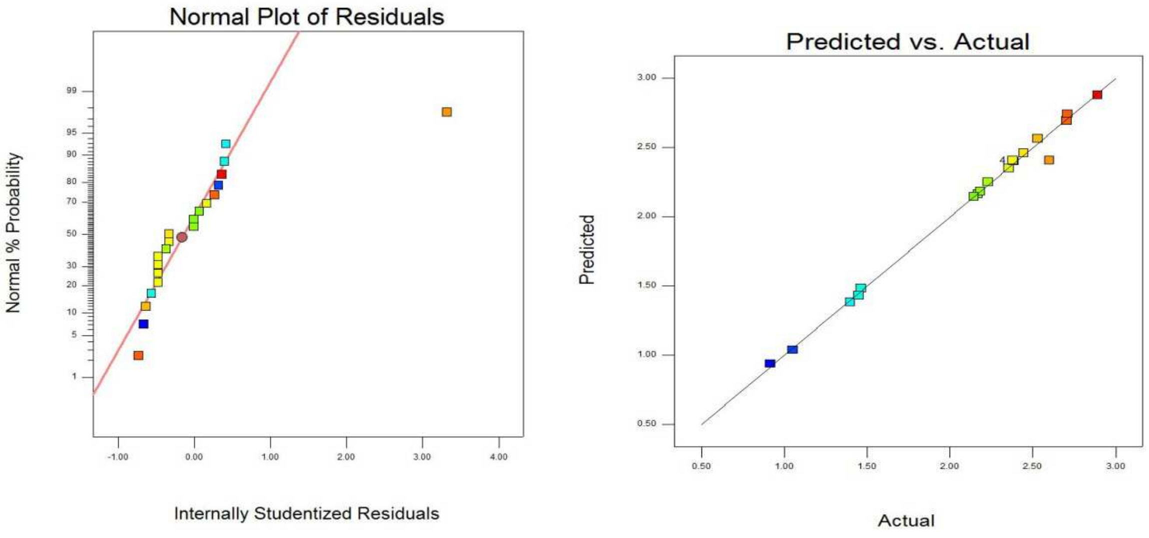

Figure 4.2 For cutting speed a) Residual plot b) predicted and actual value

The residual analysis as a primary diagnostic tool is also done. Normal probability plot of residuals has been drawn (Figure 4.2 a). All the data points are following the straight line. Thus the data is normally distributed. It can be seen from Figure 4.2 b that all the actual values are following the predicted values and thus declaring model assumptions are correct.

4. Conclusions

The important conclusions drawn from the present study are summarized below:

1. For cutting speed, Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D), are the significant factors. The higher is the current setting, higher the cutting speed.
2. For cutting speed, Pulse off time (B), Peak current, Spark gap set voltage (D) and few interactions BC and quadratic terms (A2, B2, C2) are significant.
3. The experimental values are in good agreement with the predicted values, thus the results are validated.

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