Multi-Objective Parametric Optimization for Non-Conventional Machining of Inconel 825 – for an Industrial Application

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Inconel and titanium based alloys are hard, high temperature resistant and high strength materials finding wide application in aerospace, marine, food processing and nuclear industries. The conventional machining of these materials results in higher cutting forces and excessive tool wear. Wire cut electrical discharge machining (WEDM) being one of the popular non-conventional machining processes is used for macro and micro machining of hard and high strength materials. In this work, an experimental analysis and response surface modelling of WEDM process of Inconel 825 has been carried out. The surface roughness (Ra) and material removal rate (MRR) are two common performance parameters for accessing the ability of WEDM process. Pulse on time (T_on), pulse off time (T_off), peak current (I_p) and servo voltage (SV) are used as process parameters. Response surface methodology (RSM) modelling between inputs-output relationships has been obtained. The developed full quadratic model with R² value of 92.06% and 95.62% for Ra and MRR respectively, produces less percentage error. The relationship between process responses and input factors are analyzed with 3D surface plots. The multi-objective optimization of non-conventional machining of Inconel 825 using genetic algorithm (GA) provides 21 Pareto-optimal fronts. An optimization table is generated for use in manufacturing industry for the production of components of desired surface roughness with maximum MRR.

Keywords: Inconel 825, WEDM, Optimization, Surface Roughness, MRR.

Introduction

In the family of Ni-based super alloys Inconel 825 is widely used in aerospace, marine, chemical and food processing industries. Due to work hardening nature of Ni-based alloys non-conventional machining processes (such as electrical discharge machining (EDM) and wire cut EDM) is commonly used for macro and micro machining of components. The literature study reveals that most of WEDM machinability studies have been carried out on steels and other alloys and very few on nickel based alloys such as Inconel 825. In this work, an experimental analysis and response surface modelling of WEDM process of Inconel 825 has been presented. The surface roughness (Ra) being quality of job produced and material removal rate (MRR) as economic aspects of the machining are two investigating process responses. The optimum process parameters are obtained for simultaneously optimizing Ra and MRR using genetic algorithm (GA). The optimized process parameters will be useful for manufacturing industry to produce components of desired surface roughness with maximum MRR.

Wire cut edm of inconel 825

Inconel 825 was used as work material for experimentation and it has the composition of Ni (38-46%), Fe (22%), Cr (19.5-23.5%), Mo (2.5-3.5%), Cu (1.5-3%) and Ti (0.6-1.2%). The size of the work piece used was 75 mm x 55 mm x 15 mm. Brass wire of 0.25 mm diameter was used as electrode. Machining experiments are performed on CNC wire cut EDM (Model: Electronica Sprintcut 734). The table movements are controlled by servo system with an accuracy of 1 μm. From the review of literature, four process parameters namely pulse on time (T_on); pulse off time (T_off), peak current (I_p) and servo voltage (SV) are chosen for investigation in the present study. All process parameters are considered at three different levels as T_on (factor A) in μs: (108, 112, 116); T_off (factor B) in μs: 48, 54, 60; I_p (factor C) in Amp: 200, 210, 220; servo voltage, SV (factor D) in volt: 15, 20, 25. The other parameters like wire...
feed, wire tension, servo feed, etc. are kept constant. The experiments are performed with 4 control factors with 3 levels. Since the full factorial experimental design requires large \((L^3=3^4=81)\) number of experiments, Box-Behnken \(L_{27}\) experimental design was used. The CNC program was developed for linear cutting of 100 mm length.

A constant spark gap of 0.30 mm is maintained between the wire and the work specimen. The material removal is affected by localized melting and vaporization on both electrode and work material. The continuous flushing of dielectric (deionized water) medium removes the eroded debris. The wire once used is not fed again due to variation in dimensional accuracy. Fig. 1 shows schematic arrangement and experimental set up of WEDM process of Inconel 825. The two most important performance measures in WEDM are material removal rate (MRR) and surface roughness (\(Ra\)) of the workpiece and material. The MRR (also known as cutting rate) is evaluated using the relationship given in Eq. (1).

\[
MRR = \frac{\text{Volume of material removed/cutting time}}{\text{MRR (mm}^3\text{/min)}} = (k_t \times t \times l)/t_c,
\]  

(1)

Here, \(k_t\) is kerf width of the machining in mm, \(t\) is the thickness of the specimen in mm and \(l\) is the length of machining in mm. The kerf width is measured at five places across the length of cut, using Leica microscope (DM3000:10X zoom) with Leica Q winv3 software and the average of them is considered. The machined workpiece is cut into pieces and its surface roughness measured using 3D profilometer (Taylor Hobson-Form Talysurf 50) which measures \(Ra\) in \(\mu\text{m}\). Three readings of surface roughness were taken and the average is considered. The value of surface roughness varied between 1.344 and 2.796 \(\mu\text{m}\).

**RSM modelling for Ra and MRR**

Response surface methodology (RSM) is a popular mathematical and statistical technique used for modelling, analysis and optimization of multi variable problems. RSM obtains the relationships between one or more measured responses and input parameters. The measured responses are analyzed and mathematical model is developed with best fits. The fit summary for \(Ra\) and MRR suggests a quadratic relationship that is robust and incorporates all terms (i.e., linear, interaction and square) with higher \(R^2\) value. The generalized model equation can be expressed in Eq. (2).

\[
Y_u = b_o + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j}^{k} b_{ij} X_i X_j
\]  

(2)

Where \(Y_u\) is the response and the \(X_i\) (1, 2, ..., \(k\)) are coded level of \(k\) quantitative variables. The coefficient \(b_o\) is the free term, the coefficients \(b_i\) are the linear terms, the coefficients \(b_{ii}\) are the quadratic terms, and the coefficients \(b_{ij}\) are the interaction terms. The RSM model is obtained using MINITAB17® statistical software for the experimental data sets (Table 1). The obtained model equations for \(Ra\) and MRR with their \(R^2\) values are given in Eq. (3) and (4) respectively.

\[
0.598I_p - 0.150SV - 0.00217T_{on}^2 - 0.00486T_{off}^2 - 0.00561I_p^2 + 0.00634SV^2 + 0.00086T_{on}T_{off} + 0.00258T_{on}I_p + ...
\]  

Fig. 1—WEDM process of Inconel 825
0.00131T_{on}SV + 0.00073T_{off}I_p -
0.0020T_{off}SV + 0.00163I_pSV ... (3)

\[ R^2 = 92.06\% \]

\[
MRR = -9.0 - 0.76T_{on} + 1.351T_{off} - 0.001I_p \\
+ 0.517SV + 0.00333T_{on}^2 \\
-0.00862T_{off}^2 - 0.0011I_p^2 + 0.0011SV^2 \\
- 0.0021T_{on}T_{off} + 0.00126T_{on}I_p \\
+0.00127T_{on}SV - 0.00129T_{off}I_p -
0.0092T_{off}SV - 0.0001I_pSV ... (4)
\]

\[ R^2 = 95.62\% \]

The predictive capability of the models shows minimum average percentage error as 4.49 % and 3.9% for \( R_s \) and \( MRR \) respectively. The maximum percentage error of \( R_s \) is 12.76 % and for \( MRR \) is 11.18%. The established mathematical models can be successfully used in determining surface roughness and material removal rate with significant accuracy.

**Model analysis**

In WEDM process, the surface quality and material removal rate are important performance measures.

### Table 1—Optimized process parameters recommended for industrial applications

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>( T_{on} (\mu s) )</th>
<th>( T_{off} (\mu s) )</th>
<th>( I_p (A) )</th>
<th>( SV (V) )</th>
<th>( MRR ) (mm³/min)</th>
<th>( Ra ) (µm)</th>
</tr>
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<tr>
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<td>108.09</td>
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<td>21.56</td>
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because of their crucial effect on industrial economy for production of quality components. The effects of individual process parameters as well as their interactions on the performance measures have been studied here with the help of 3D surface plots. Fig. 2 (a) shows the interaction plot between \( T_{on} \) and \( T_{off} \) that affects surface roughness. Low values of \( T_{on} \) and \( T_{off} \) give rise to minimum Ra. It can be argued that at low values of \( T_{on} \) (108–110 µs) smaller crater is generated on the workpiece surface due to reduced melting and evaporation rate 5. Fig. 2 (b) shows the interaction between \( T_{on} \) and SV and it reveals that higher value of SV improves Ra. The increase in servo voltage decreases the gap between workpiece and the wire. This reduces discharge current and hence the melting rate. This leads to reduction in the surface roughness of the workpiece. It is clear from Fig. 2 (b) that low values of pulse on time (100–110 A) and higher values of spark gap voltage (23–25 V) give rise to minimum surface roughness. Fig. 2 (c) shows the SEM image of the workpiece for the lowest surface roughness \((T_{on}=108 \mu s, T_{off}=54 \mu s, I_p=210 A, SV=25 V)\). The lowest value of surface roughness obtained was 1.334 µm. Fig. 2 (d) shows the variation in contour plot for MRR with respect to \( T_{on} \) and \( T_{off} \). Increased MRR is obtained at higher \( T_{on} \) and lower \( T_{off} \). The higher \( T_{on} \) enhances the spark generation removing more material. Fig. 2 (e) shows the variation of \( I_p \) on MRR. It is found that at higher \( T_{on} \) and higher \( I_p \), MRR increases due to enhanced melting and evaporation rate. The optimization of process parameters is performed using genetic algorithm (GA) being soft computing based global optimization technique.

**Multi Objective Optimization Using GA**

Genetic algorithm (GA) is one of the popular optimization techniques evolved by the process of natural genetics that works on the principle of ‘survival of the fittest’ 10. The fitness functions are derived from model equations and are optimized using three basic genetic operations, namely reproduction, crossover and mutation, in an iterative (generation by generation) manner. A large set of initial solutions (called population) are generated within the search space. Each solution in the search space (i.e., string or chromosome) is assigned to fitness function and the function value evaluates how close the string is near to the desired objective. The process is repeated till the function value reaches to the desired accuracy. The available literature
The single objective optimization of single objective case (i.e., $Ra$ and $MRR$ individually) will usually result in two different optimal solutions. The optimum process parameters obtained for optimizing one particular objective function do not provide good result for other objective functions. For manufacturing industry involved in producing quality components economically, both $Ra$ and $MRR$ are found to be equally important. The surface roughness ($Ra$) is to be minimized and $MRR$ to be maximized. Hence multi-objective optimization using GA is employed in this work. The formulation of the problem is as follows:

- **Objective 1**: Minimize $Ra$ ($T_{on}$, $T_{off}$, $I_p$, $SV$): This is an important criterion for assessing the quality of
the surface produced. The lower surface roughness value provides better quality.

- Objective 2: Maximize MRR ($T_{on}$, $T_{off}$, $I_p$, $SV$): The increased metal removal rate takes minimum machining time for completion of the job. This objective is to be maximized for increased productivity.

The process variables are bounded with its lower bound (LB) and upper bound (UB) limiting the search space. The LB and UB are given as $108 \leq T_{on} \leq 116$; $48 \leq T_{off} \leq 60$; $200 \leq I_p \leq 220$ and $15 \leq SV \leq 25$. The problem is optimized using GA tool box of MATLAB. The different GA parameters viz., population size; cross over probability; mutation rate; selection function and number of generation, are crucial to obtain the best optimum parameters. Researchers have not given any specific recommendation of these parameters. The selected GA parameters of present optimization work are: (i) number of population=20, (ii) number of iterations=500, (iii) cross over probability=0.7 and (iv) mutation probability=0.05. The multi-objective optimization of WEDM of Inconel 825 is carried out using non-dominated sorting genetic algorithm (NSGA-II) in MATLAB 7.10®. Fig. 3 shows non-dominated Pareto fronts obtained during simultaneous optimization of two conflicting objectives (i.e., minimize $R_a$ and maximize $MRR$). The Pareto front is defined as the border between feasible (upper part) and infeasible region (lower part). The shop floor engineer can select optimal combination of parameters from the Pareto-optimal solution set, depending on the requirements. The selection of optimal solution depends on number of factors like user’s choice and nature of the problem.

**Recommendation for Industrial Application**

In modelling and optimization of machining processes, researchers usually obtain optimum process parameters for minimum $R_a$ and maximum $MRR$. In case of multi objective optimization a combined weighted objective function is optimized to obtain optimum process parameters. The industries usually need to produce components economically for different value of surface roughness as per design requirement. The surface roughness requirement depends on the use or application of the component. The production of high quality surface (i.e., low surface roughness value) occurs at low $T_{on}$ which leads to low $MRR$. The simultaneous optimization of both objectives provides 21 Pareto-optimal fronts. The optimal combination of cutting conditions is obtained for all Pareto optimal solutions at which the surface roughness is minimum and $MRR$ is maximum. It is presented in Table 1. This helps to select the optimum cutting conditions with higher metal removal rate for desired value of surface roughness of the work piece to be produced. This will be useful for shop floor engineers. For instance, if the manufacturing industry needs to produce a component with $R_a \leq 1.50 \mu m$, the Table 1 suggests appropriate process parameters that would yield the maximum $MRR$ satisfying the desired surface finish limit. Referring to Table 1, serial number 12 gives optimum values of process parameters ($T_{on}=112.50\mu s$, $T_{off}=59.85\mu s$, $I_p=218.69A$ and $SV=20.32V$). The corresponding value of $R_a$ and $MRR$ obtained are 1.48 $\mu m$ and 3.30 mm$^3$/min respectively. The confirmation experimentation of serial number 12 was carried out for the optimum combination of cutting conditions obtained. The actual surface roughness and $MRR$ obtained were 1.52 $\mu m$ and 3.28 mm$^3$/min respectively. The validation experimental results indicate that the developed GA model can closely predict the performance of WEDM process. Thus Table 1 could be used for obtaining optimum parameters for different values of $R_a$ ranging from 0.7 to 2.08. This approach is found to be an effective tool and can be developed with minimum effort.

**Conclusions**

In this work, an experimental study on Inconel 825 using WEDM process has been carried out. The machining experiments were performed with four process parameters ($T_{on}$, $T_{off}$, $I_p$, $SV$) set at three levels using Box-Behnken $L_{27}$ experimental design was used. The surface roughness ($R_a$) and material removal rate ($MRR$) were considered as two response characteristics. Process modelling using RSM and parametric optimization using GA were carried out.
On the basis of result obtained the following conclusions are drawn:

- The $R^2$ value of developed mathematical model for surface roughness ($R_a$) and material removal rate (MRR) are 92.06% and 95.62% respectively confirming the effectiveness of the model.
- The predictive performance of RSM model provides an average percentage error as 4.49% and 3.9% for $R_a$ and MRR respectively and maximum error as 12.76% and 11.18% for $R_a$ and MRR respectively.
- The pulse-on time ($T_{on}$) is the most influencing factor for surface roughness and material removal rate during WEDM of Inconel 825. The lower value of SV leads to lower melting of material and hence deteriorates $R_a$. The peak current ($I_p$) does not play a significant role during machining.
- The higher value of $T_{on}$ and $I_p$ is found to be responsible for generation of bigger craters on the workpiece surface, due to increase in melting and evaporation rate resulting in increased MRR.
- The results of multi objective optimization for minimizing $R_a$ and maximizing MRR using GA provide 21 numbers of Pareto-optimal fronts. The optimized results may be used as a guideline by manufacturing industry for selection of optimum process parameters for producing desired surface roughness of the component with maximum MRR. This will be useful for shop floor engineers. The approach is found to be an effective tool and can be developed with minimum effort.

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References