Multi-Criteria Optimization of Aerospace Alloys in WEDM Using TOPSIS

SANJAY HERALGE¹, UMASHANKER GUPTA² and JAMIL DABIR³

¹,³Mechanical Engineering Department, Walchand College of Engineering, Sangli, India
²Defence Metallurgical Research Laboratory, Hyderabad, India
Email: heralgesanjay@gmail.com

Abstract. Wire EDM is commonly used for machining of complex profiles in hard and exotic materials. In the present work the key performance of Wire EDM such as wire cutting speed, surface roughness and cut width in machining of three different aerospace class materials such as near beta titanium alloy, forged nickel base alloy and aged aluminum alloy are studied. Apart from electrical parameters, the wire with zinc coated brass and plain brass are used. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is the Multi-Criteria Decision-Making method used for selecting the best setting of control parameters. Parameter sets are ranked from best to worst based on the performance score. Zinc coated wire outperforms the brass wire almost for every response variable in case of Ni and Ti alloy while with Al it is as good as plain wire.

Keywords. Wire EDM, TOPSIS, Cutting speed, Kerf width, Surface roughness

1. Introduction

Wire Electro-Discharge Machining (WEDM) is a non-conventional machining process, which is popularly used in industries for precision machining of difficult to machine electrically conductive materials. In Wire EDM, wire is used as tool for removing material from intended workpiece. Thousands of electrical discharges per second is generated between tool and work, which produces tiny craters by melting and evaporation on work material.

F. Nourbaksha et al. [1] carried out the Wire EDM of Ti6Al4V and found that using zinc coated wire gives better surface finish and high cutting speed. Mohapatra et al. [2] optimized gear cutting of Inconel 718 with wire EDM by using TOPSIS method. Prohaazka et al. [3] investigated the impact of Wire EDM on annealed non-alloyed steel with minimum carbon content using magnesium, zinc and tin wire. They mentioned term called as “Heat sink effect” which states that in zinc coated wire during the sparking zinc evaporates keeps core away from damage and keeps it cool. Muniappan et al. [4] analyzed the effect of machining parameters on kerf width and surface roughness using TOPSIS Multi-Criteria Decision Making (MCDM) strategy to evaluate ideal Wire EDM machining parameter for aluminum hybrid composite machining with the use of brass wire. S. Dhale et al. [5] compared the performance of plain brass wire and zinc coated wire on Inconel 718 material. MRR with zinc coated wire observed to be higher than brass wire but the increase in the machining speed results into the higher surface roughness also. Santhanakumar et al. [6] optimized micro wire electrical discharge machining (µ-WEDM) while machining of Ti alloy using TOPSIS with hybrid approach and response surface methodology. Jangra et al. [7] carried out the study with Wire EDM trim cut on materials such as HCHCr steel alloys, WC-Co composite, Monel-400 and Nimonic-90. They studied the effect of material properties on WEDM. N.Chakladar [13] used TOPSIS with AHP (Analytic Hierarchy Process) and studied their combined effect on selection of process in non-traditional machining process and also discussed how TOPSIS combined with AHP satisfies the multi-criteria decision making (MCDM). A.Singh [14] adopted TOPSIS with Taguchi method for optimization of multiple parameters of surface roughness machined with GFRP polyester composites and concluded why TOPSIS is best method for MCDM. The approach used in TOPSIS is ranking based which further used to choose the best and worst alternatives from positive (as near as possible to the ideal solution).
and negative (as far as possible from the ideal solution) ideal solutions. TOPSIS is relatively simple to understand and implement in case Multiple Criteria Decision Making problem. Assigning weights to normalized value of outputs or responses based on application or requirement and calculating performance score, which is used to rank the alternative, this makes TOPSIS very easy to understand and implement in real life problem. Therefore, in this study also TOPSIS with FAHP (Fuzzy Analytic Hierarchy Process) is used for selection of process parameters. From the past literature, it is concluded that selection as well as optimization of proper process parameter is very important in manufacturing industry. The effect during machining would be adverse if improper machining parameters have been selected. There are very limited works in Wire EDM of aerospace material is available. Therefore, the present work focused on optimization of three aerospace alloys using TOPSIS and their performance has been compared on cutting speed, kerf width or cut width and surface roughness. The generated machining data will be useful for academic and industries involved in processing of aerospace materials.

2. Materials and Methods

The experiment was performed on ‘Electronica Ultracut’ wire EDM using power pulse mode on near beta Ti alloy for structure applications, forged Ni based alloy for turbine disc application and aged Al alloy for structure applications. Two types of wires, uncoated brass wire or plain wire (UC) and zinc coated wire (C) of 0.25mm diameter are used. Taylor Hobson’s contact type surface roughness profilometer with 0.8mm cut off and ISO gaussian filter used for measuring surface roughness of workpiece. For reading purpose, each surface measured and total six measurements were taken and then the results are averaged. Kerf width or width of cut are measured using optical profile projector. Samples are machined for straight 15 mm length in 10 mm thickness. The parameters for study are carefully selected from literature and to cover the range of parameters specified in machine manual. Table 1 shows the parameter chosen for the study, where pulse on time (T_{on}), current (I) and type of wire are varied and other parameters are kept constant at particular values considering minimum wire breakage. The Pulse on time is varied at three different level and current with two levels. In ‘Electronica Ultracut’ wire EDM machine current is available in two settings low current (11) and high current (12) and the values 11 and 12 are not current in amperes

| Sr No | Parameters       | Value            |
|-------|------------------|------------------|
| 1     | Pulse on time (µsec) | 110,120 and 130 |
| 2     | Pulse off time (µsec) | 50              |
| 3     | Servo voltage (Volts) | 20              |
| 4     | Wire tension (N)   | 15               |
| 5     | Wire feed (m/min)  | 8                |
| 6     | Water pressure (Kg/cm²) | 4              |
| 7     | Servo feed (mm/min) | 25              |
| 8     | Current           | 11,12            |
| 9     | Type of wire      | Plain brass and zinc coated |

To understand the difference in three metal alloys selected for study their physical and mechanical properties are listed in table 2 such that one can compare the properties easily. Thermal conductivity, tensile strength, young’s modulus, melting point and density these are the properties listed in table 2 for three alloys.
Table 2. Physical and mechanical properties of work materials.

| Work Material          | Properties of work material |
|------------------------|-----------------------------|
|                        | Thermal conductivity (W/mK) | Tensile strength (MPa) | Young’s modulus (GPa) | Melting point (°C) | Density (gm/cm³) |
| Near Beta Ti alloy     | 7.8                         | 930                    | 110                   | 1642              | 4.65            |
| Forged Ni based alloy  | 11.72                       | 780                    | 220                   | 1320-1365         | 8.19            |
| Aged Al alloy          | 116-170                     | 172-476                | 73.8                  | 543               | 2.84            |

3. Results and Discussion

Table 3 illustrates the experimental plan and obtained performance data. Each alloy was machined on two current settings and on each current pulse on time varied to three levels with coated and uncoated wire. Three responses cutting speed (Vc), Kerf width (KW) and Surface roughness (Ra) for all three alloys are listed in table is such way that in single table itself one can draw meaningful conclusion. Total 12 experiments are carried on each metal alloys and above three responses are measured for every experiment and thus total 36 experiments are carried out in entire experiment and all are shown in table 3.

Table 3. Experimental data obtained for Ti, Ni and Al alloy.

| Control Factors | Ti alloy | Ni alloy | Al alloy |
|-----------------|---------|---------|---------|
| Vc (mm/min)     | KW (µm) | Ra (µm) | Vc (mm/min) |
| 1               | 0.923   | 0.3424  | 2.3100  |
| 2               | 1.25    | 0.3872  | 3.0248  |
| 3               | 1.25    | 0.3853  | 2.9410  |
| 4               | 1.0018  | 0.3479  | 2.4857  |
| 5               | 1.49    | 0.4102  | 3.3575  |
| 6               | 1.5     | 0.421   | 3.4075  |
| 7               | 1.03    | 0.3421  | 2.2337  |
| 8               | 1.3     | 0.3839  | 3.1144  |
| 9               | 1.32    | 0.3879  | 2.9465  |
| 10              | 1.12    | 0.3422  | 2.3577  |
| 11              | 1.6     | 0.4056  | 3.2515  |
| 12              | 1.61    | 0.4081  | 3.2504  |

3.1 Effect of TON and type of wire on cutting Speed (Vc)

Cutting speed directly affects the productivity of machining process. Figure 1 shows the wire cutting speed of all metal alloys with coated and uncoated wire at high current setting (12). As the TON increases the Vc increases for all three metal alloys and further better with coated wire. The reason for higher cutting speed with coated wire is ‘Heat sink effect’ i.e. increase in conductivity within the sparking gap due to the fast melting and vaporization of the zinc particles. This leads to improved flushing condition results in increase in spark gap width, which protects the brass core from damage and also maintain the lower temperature at the core [3].
Figure 1. Effect of $T_{ON}$ and type of wire on cutting speed.

Among three material, Al alloy exhibits higher cutting speed than other alloys. For Al alloy cutting speed with coated wire and uncoated wire is almost same. Figure 1 states that cutting speed of: Al > Ti > Ni this may be because the Al alloys has lowest melting point and highest conductivity among all three metals which leads easy and more metal removal because of intense sparking. As the behavior of cutting speed at low current is same as that of in high current only the value of cutting speed less in low current hence only data machined with high current is represented in graph which is sufficient to understand the impact of control factors on response variables. If thermal conductivity of material is high then increase in fraction of heat transfer to the most of the bulk material and therefore less melting and evaporation of work material takes place [7] which is here in case of Al alloy where little increase in cutting speed is observed with increases in $T_{ON}$. Whereas Ti has low thermal conductivity, which results more increase in cutting speed with increase in $T_{ON}$.

3.2 Effect of $T_{ON}$ and type of wire on Kerf width (KW)

The amount of material which is wasted while machining in the gap of wire and workpiece is called as kerf width. Due to this kerf width, we cannot get desired dimensions which decreases the dimensional accuracy of machined part. Therefore, the kerf width should as minimum as possible. The kerf with is equals to wire diameter added with 2 times of spark gap. As $T_{ON}$ increases, the kerf width also increases as shown in figure 2. Machining with zinc coated wire results in lesser kerf width than with uncoated brass wire. In the figure 2 below, kerf width at high current setting (12) is represented.

Figure 2. Effect of $T_{ON}$ and type of wire on Kerf width.
Kerf width is also dependent on the work material thermo-physical properties such as melting point, thermal conductivity etc. As the thermal conductivity is less more material will be melted and evaporate as compare to the material with higher thermal conductivity. Hence, in Ti alloy kerf width is more than other two metal alloys.

3.3 Effect of $T_{ON}$ and type of wire on Surface roughness (Ra)

In WEDM process surface roughness of machined surface is depends on the size and depth crater produced after melting as well as expulsion of work material. As shown in figure 3 as the $T_{ON}$ increases, the discharge energy increases which leads to large and deep craters results in more surface damage and increased surface roughness.

If the work material have low melting point, high discharge energy results into overheating and evaporation of molten metal forming gas bubble that explodes when discharge ceases. Hence Al alloy having low melting temperature has more surface roughness with both coated and uncoated wire whereas Ti and Ni alloy with high melting point has less surface roughness than Al alloy. Surface roughness when machined with coated wire is less than uncoated wire for Ti and Ni alloy but for Al alloy surface roughness with coated wire is more. As per previous literature in some cases with use of zinc coated wire surface roughness was improved [1] and, in some cases, surface roughness was not improved like in work of Kapoor et al. [10] hence there is no uniformity in results with coated wire that states that the surface roughness always improves when coated wire is used. Improved surface roughness with the zinc coated wire may be due to the existence of zinc and this provides higher strength to wire and this wire maintains itself straight under vibration [1]. In addition to this eventual evaporation of zinc coating leads to less debris in spark gap results in minimum secondary sparking.

3.4 Multi-Criteria Decision Making (MCDM)- TOPSIS Optimization

TOPSIS-Technique for Order Preference by Similarity to Ideal Solution is closest to the ideal alternative and so far from the negative ideal. Table 4 consist of summarized data from TOPSIS method where the data from every step is represented in table format for easy understanding and $V_j^+$ and $V_j^-$ are listed below end of respected column for better view and understanding. Overall, all the data from TOPSIS steps are summarized in single table named table 4. The TOPSIS method consists of the following step [2, 4, 6, 13, 14, 15]:

![Figure 3. Effect of $T_{ON}$ and type of wire on Surface roughness.](image_url)
Table 4. Multi-objective decision making using TOPSIS method.

| Ex No | Wire | I | TON | Vc   | KW   | Ra   | Si+  | Si-  | Pi   | Rank |
|-------|------|---|-----|------|------|------|------|------|------|------|
| 1     | UC   | 11| 110 | 0.013647 | 0.056969 | 0.162958 | 0.011494 | 0.250801 | 0.956178 | 3   |
| 2     | UC   | 12| 120 | 0.018482 | 0.064423 | 0.213385 | 0.056559 | 0.238572 | 0.80836 | 7   |
| 3     | UC   | 13| 130 | 0.018482 | 0.064107 | 0.207473 | 0.050689 | 0.239619 | 0.825395 | 5   |
| 4     | UC   | 12| 110 | 0.014812 | 0.057884 | 0.175353 | 0.019943 | 0.248278 | 0.925647 | 4   |
| 5     | UC   | 12| 120 | 0.022031 | 0.06825  | 0.236859 | 0.080105 | 0.237693 | 0.747937 | 11  |
| 6     | UC   | 12| 130 | 0.022178 | 0.070047 | 0.240387 | 0.083857 | 0.238113 | 0.73955  | 12  |
| 7     | C    | 11| 110 | 0.01523 | 0.05692  | 0.15758  | 0.008576 | 0.251537 | 0.967031 | 1   |
| 8     | C    | 11| 120 | 0.019221 | 0.063874 | 0.219709 | 0.062686 | 0.237695 | 0.791312 | 8   |
| 9     | C    | 11| 130 | 0.019517 | 0.06454  | 0.207861 | 0.051036 | 0.239659 | 0.824433 | 6   |
| 10    | C    | 12| 110 | 0.01656 | 0.056936 | 0.166323 | 0.011356 | 0.252187 | 0.956912 | 2   |
| 11    | C    | 12| 120 | 0.023657 | 0.067484 | 0.229381 | 0.072575 | 0.237585 | 0.766007 | 10  |
| 12    | C    | 12| 130 | 0.023805 | 0.0679   | 0.229304 | 0.07256  | 0.237638 | 0.766085 | 9   |

Vj+ = 0.023805, Vj- = 0.013647

Step 1: Calculate normalized Matrix (normalized values) using below formula, $X_{ij}$ represents the actual value of output in cell. The next is to calculate the $\sum_{i=1}^{n} X_{ij}^2$ that is sum of all the values in single column then use it in formula given below where n=1,2,..12 which are number of experiment or number of alternatives in this study and repeat this for every column to prepare matrix. Considering cutting speed as beneficial attribute due to higher values while Ra and KW as non-beneficial because of smaller values.

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$$

(1)

Where i represents rows or number of experiments and j represents column or number of criteria or output responses.

Step 2: Calculate the weight for every response variable. In this study, the Fuzzy Analytic Hierarchy Process (FAHP) with Geometric mean [11] is used to calculate the weight. The inter-relations used to calculate the weight is: if Vc = x then Kerf width = 5x, if Cutting speed (Vc) = x then Surface roughness (Ra)= 7x and if kerf width (kw)= x then surface roughness= 5x. These relations can be changed based on customer requirement and area of application. In this study, these relations are taken in order to have minimum surface roughness, minimum kerf width and maximum cutting speed. The relations are managed in such way that more weightage will be assigned to surface roughness then to kerf width and less to cutting speed.

Based on this the weights (Wj) obtained for Vc= 0.0667, KW= 0.2198 and Ra= 0.7134

Step 3: Calculate the weighted Normalized matrix, by multiplying weights to normalized value

$$V_{ij} = \bar{X}_{ij} \times W_j$$

(2)
Where $W_j$ is weight calculated in step 2, $X_{ij}$ is the normalized value in for $i^{th}$ row or experiment from $j^{th}$ column or output response from step 1 calculated using equation (1) and $V_{ij}$ is the weighted normalized value for $i^{th}$ row or experiment from $j^{th}$ column or output response. The values in the column of $V_c$, $KW$ and $Ra$ in table 4 are weighted normalized values.

Step 4: Select the ideal best ($V_j^+$) and ideal worst ($V_j^-$) value for every column in matrix or table that is from $V_{ij}$ calculated in step 2 with help of equation (2). Ideal best is maximum value for beneficial attribute and minimum value for non-beneficial attribute whereas ideal worst is minimum value for beneficial attribute and maximum value for non-beneficial attribute from every column or output response. For example, $V_j^+$ for surface roughness is minimum value of $V_{ij}$ form surface roughness column and for cutting speed it is maximum value of $V_{ij}$ from cutting speed column.

Step 5: Calculate the Euclidian distance from the ideal best

$$S_i^+ = \left[ \sum_{j=1}^{m} (V_{ij} - V_j^+) \right]^{0.5}$$

(3)

Where $S_i^+$ the Euclidian distance from the ideal best, $V_{ij}$ is weighted normalized value in respective cell and $V_j^+$ is the ideal best value of respective column as shown in table 4.

Step 6: Calculate the Euclidian distance from the ideal worst

$$S_i^- = \left[ \sum_{j=1}^{m} (V_{ij} - V_j^-) \right]^{0.5}$$

(4)

Where $S_i^-$ is the Euclidian distance from the ideal worst, $V_{ij}$ is weighted normalized value in respective cell and $V_j^-$ is the ideal worst value of respective column as shown in table 4. Here $m=3$ ie. for $V_c$, $KW$ and $Ra$ column.

Step 7: Calculate the Performance score ($P_i$) and rank this to take decision.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

(5)

Where ($P_i$) represents the performance score and $S_i^+$ and $S_i^-$ calculated from equation (3) and (4) respectively. Larger performance score represents best choice among all alternatives.

Table 4 shows the data obtained by TOPSIS method for Ti alloy where ranking is done by decreasing order of performance score obtained from equation (5) which are: 7-10-1-4-3-9-2-8-12-11-5-6 where it is understood that the experiment no. 7 which is ranked 1st is first best choice which will give minimum surface roughness, minimum kerf width and maximum cutting speed. Next one is experiment no. 10 which is ranked as 2nd is second best choice. Optimized values for Ti alloy are from the 1st best choice experiment no.7 having the highest performance score. The values are current setting 11, coated wire and $T_{on}=120$. Same procedure was followed to calculate the performance score for both Ni and Al alloy. The experiment numbers, their sequence and values are same for all three alloys as given in table 3 (also in table 4) and their response output is also given in table 3. Hence individual tables for Ni alloy and Al alloy representing calculation of TOPSIS method are not shown in this paper only their experiments number are ranked based on the performance score after following
same steps. For Ni alloy the experiment numbers are ranked in descending order of their Performance score as: 10-7-4-1-5-9-8-11-3-12-2-6 which indicates that experiment no. 10 is first best choice. Optimized values for Ni alloy are from the best choice experiment no.10, which are current setting 12, coated wire and $T_{ON}=110$. For Al alloy the experiment numbers are also arranged in descending order of their Performance score as: 1-7-4-10-8-9-2-3-5-12-11-6 where experiment number 1 is first best choice. Optimized values for Al alloy are from the best choice experiment no.1, which are current setting 11, uncoated wire and $T_{ON}=110$

It is observed that the experiment number 7 is in first two best choices in every metal alloy whereas experiment number 6 is last best choice (worst) for all metal alloys.

4. Conclusions
In present work, an empirical study in Wire EDM has been conducted on three different metal alloys namely near beta Ti alloy, forged Ni alloy and aged Al alloy. Cutting speed, kerf width and surface roughness were the performance characteristics. With the help of TOPSIS all experiments were ranked based on their performance score where it was observed that experiment number 7 was there in top 2 best choices in every metal alloys which shows that the machining with coated wire leads to desirable results. Results shows that with increase in $T_{ON}$ cutting speed, surface roughness and kerf width increases which is due to the increased discharge energy lead to high material removal. Coated wire due to its zinc coating that is having less melting point evaporates early which leads to increased spark gap to improve flushing efficiency results into high cutting speed and decreased kerf width. In future, work the surface integrity in wire EDM using coated wire can be taken up.

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