Experimental Investigation of Uncoated Electrode and PVD AlCrNi Coating on Surface Roughness in Electrical Discharge Machining of Ti-6Al-4V

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1. INTRODUCTION

Titanium and its alloys are widely used in various fields including aerospace, nuclear, medical, etc. It is highly difficult to process such materials with traditional machining methods due to the higher strength. Electrical discharge machining (EDM) is commonly used to process this group of materials. In EDM, the machining surface quality and the machining productivity is not high [1]. Many technical solutions have been implemented to improve the machining efficiency of EDM including optimization of technological parameters, new electrode material or electrode surface layer and vibration in EDM. It has shown that the utilization of coated electrodes EDM is a great promising solution to improve machining productivity and quality. It can reduce the wear of tool electrode and production costs. However, research works on EDM using new electrode materials are mainly focused with powder metallurgical electrodes. The usage of coating electrodes are still very little. In addition, the physical and mechanical properties of the material layer of the electrode surface will directly affect the spark formation process to enhance the machining productivity and quality. Hence it is necessary to clarify the effectiveness of using coated electrodes in EDM process.

Extensive research were performed to evaluate the machinability of the electrode in EDM [2]. Many types of electrode materials (Al, Cu, Cu-W and brass) have been investigated in tool steel machining by EDM [3]. The Cu-W could produce lower surface roughness (Rₐ) in EDM [4]. The machining capacity with Cu-W electrode is also higher than Cu and brass electrodes [5]. It was inferred that the formation of larger residual tensile stress in EDM process with conventional electrodes [6]. The electrode material used in EDM would affect the structure of the white layer on the machined surface layer consisting of austenite and residual stress [7, 8]. The different electrode materials are used in EDM to modify the surface quality [9-11]. The Rₐ and morphology of the machining surface are strongly influenced by the changes of electrode material in EDM [12]. Recent studies have used powder metallurgical electrodes in EDM to improve

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ABSTRACT

The surface texture on the EDM is an important quality indicator since it directly affects the cost of the further finishing work. The coating over the tool electrode in EDM can improve productivity, electrode wear resistance and surface quality. In the present study, the surface roughness of the EDM machined surface with coated and uncoated electrodes was evaluated. Al and AlCrNi coated Al electrode has been used for the study on machining Titanium alloy (Ti-6Al-4V). Current (I), voltage (Vₘ) and pulse on time (Ton) have been used as technology parameters under Taguchi method with regression model and optimal technology parameters. It was found as I and Vₘ are the parameters could strongly affect the surface quality. The coated tool electrode can produce better surface quality than uncoated tool electrode. The optimal technological parameters with coated and uncoated electrodes were found as I = 10 A, Ton = 500 μs and Vₘ = 40 V.

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machining efficiency with improved surface quality [13]. The TiC composite electrode can produce better surface than Cu-W electrode [14]. The powder metallurgical electrode can produce alloy layer with better surface quality and hardness[15]. The composite electrodes in EDM can be fabricated with 3D printing [16]. However, it should be required that the composition of the composite mixture of the electrode material should be corrected since it would directly affect the surface quality and machinability in EDM [17].

The surface coating technology is very popular to create a different surface material from the base material, and this improves the workability of the products. Several types of electrode materials (Cu, brass, molyden and Cu-W) coated with nickel and diamond - nickel materials have been used to investigate the improvement of TWR in EDM [18]. TWR is greatly reduced in EDM with coated electrode such as diamond - nickel coated electrode. I and T are significantly affect MRR and EWR in EDM with coated electrode [19]. The orthogonal model is determined by Taguchi - GRA, it has consistent accuracy. The higher wear resistance of the in EDM was observed with zinc coated electrode [20]. As compared to Cu electrodes, TiN or TiAIN coated Cu electrodes would be suitable for EDM better finishing [21]. The influence of parameters including V, I and T on the quality indicators in EDM was investigated. It was found that I was the most significant influential parameter. The coated electrode can significantly improve MRR, TWR, Ra and machining accuracy [22]. The roughness of the machined surface with the Cu electrode has been selected to evaluate the effectiveness of coated Cu electrode including silver, nickel, zinc and epoxy. It was found that the coated electrode can significantly improve the surface quality [23]. The zinc coated electrode provides more efficient solution than many other methods [24]. The optimal values of MRR, TWR and Ra in EDM using silver coated electrode were determined by Taguchi [25]. The optimization and regression model analysis was found with accepted accuracy of practice [26]. Taguchi method is commonly used to design experiments and analyze the effect of technology parameters on quality in the EDM using powder metallurgy electrode and coated electrode [27]. Taguchi method can be very suitable for research on the effect of new coating materials on the electrode surface on the quality parameters in EDM.

The surface roughness in EDM is an indicator directly related to the choice of the further finishing method and its machining cost. Hence a research attempt is very necessary to improve surface quality in EDM. The number of studies regarding coating electrodes and the coating materials used are still very limited. In this study, the effect of technological parameters on surface roughness (Ra) in EDM using uncoated and AlCrNi coated Al electrode was investigated. The regression model development in Taguchi has identified the regression equation of the Ra. The efficiency of the coating electrode to improve the Ra, and the quality of the machining surface at the optimum condition were also analyzed.

2. EXPERIMENTAL METHODOLOGY

The machining experiments were performed on CNC type Electro Discharge Machine manufactured by Electronics India Private Limited for machining Ti-6Al-4V alloy as shown in Figures 1 and 2. The process parameters were chosen based on low, medium and high level of process parameter available at machine. All experiments were systematically planned with four level based on Taguchi method. The levels of process parameters in this study described in Table 1. Since the work deals with three factors and four levels, L16 orthogonal array (OA) was selected in the present study to evaluate quality measurement of surface roughness (Ra). Ra of machined workpiece surface was measured by contact type surface roughness tester (Taylor Hobson machine) with the cut off length of 0.8mm.

3. RESULTS AND DISCUSSION

3. 1. Effects of Process Parameters on Ra using Analysis of Variance (ANOVA) The ANOVA analysis of Ra results to find influence of parameters on quality indicators in EDM is shown in Table 2. I (F = 161.13 with Al electrode and F = 177.69 with AlCrNi coated electrode) and V (F = 6.19 with Al electrode and F = 8.25 with AlCrNi coated electrode) had a significant effect on Ra in EDM with Al electrode and AlCrNi coated
The variation of current (I), voltage (Vg) and pulse on time (Ton) has affected Ra in EDM with Al electrode and AlCrNi coated electrode is shown in Figure 3. The higher I and Vg has lead to increase in Ra as shown in Figures 3a and 3b. The Ra was increased due to the increase of I and Vg which has led to the higher heating energy to produce larger size and depth of the craters on the machining surface [25]. The size and number of adhesion particles have been increased with larger melting and evaporation of the electrode material and workpiece [6]. As compared to Ra at I = 10 A, the maximum increase in Ra at I = 40 A was 48.9% with the Al electrode and 49.3% with AlCrNi coated electrode. The 8.3% lower Ra was found with AlCrNi coated electrode. The influence of I on Ra is much greater than Vg. The changes in Ton has resulted in negligible change in Ra with AlCrNi coated electrode as shown in Figure 3c. The Ra in EDM with Al electrode was minimum at Ton = 500 µs. The Ra was minimum at

| Input process parameters | Ra (µm) | Relative error (%) |
|-------------------------|---------|--------------------|
|                         |         | Ra (µm)            |                |
|                         |         | Experimental       | Calculated     |
| I (A) | Ton (µs) | Vg (V) | Al | AlCrNi coating | Al | AlCrNi coating | Al | AlCrNi coating |
| 10    | 100     | 40     | 6.664 | 6.111 | 6.715 | 5.954 | 0.765 | -2.576 |
| 10    | 500     | 45     | 6.683 | 6.162 | 6.914 | 6.159 | 3.452 | -0.043 |
| 10    | 1000    | 50     | 6.691 | 6.251 | 7.108 | 6.361 | 6.234 | 1.764 |
| 10    | 1500    | 55     | 6.815 | 6.294 | 7.303 | 6.563 | 7.155 | 4.277 |
| 20    | 500     | 40     | 7.781 | 6.874 | 7.774 | 6.979 | -0.085 | 1.533 |
| 20    | 100     | 45     | 8.325 | 6.976 | 8.008 | 7.217 | -3.814 | 3.448 |
| 20    | 1500    | 50     | 8.662 | 7.648 | 8.163 | 7.383 | -5.758 | -3.463 |
| 20    | 1000    | 55     | 8.981 | 7.669 | 8.401 | 7.624 | -6.461 | -0.583 |
| 30    | 1000    | 40     | 9.116 | 8.045 | 8.829 | 8.001 | -3.143 | -0.544 |
| 30    | 1500    | 45     | 9.203 | 8.338 | 9.024 | 8.203 | -1.946 | -1.617 |
| 30    | 100     | 50     | 9.412 | 8.768 | 9.300 | 8.480 | -1.189 | -3.290 |
| 30    | 500     | 55     | 9.665 | 8.946 | 9.499 | 8.685 | -1.720 | -2.914 |
| 40    | 1500    | 40     | 9.706 | 9.013 | 9.885 | 9.023 | 1.840 | 0.112 |
| 40    | 1000    | 45     | 9.783 | 9.112 | 10.122 | 9.264 | 3.465 | 1.671 |
| 40    | 500     | 50     | 10.112 | 9.313 | 10.359 | 9.505 | 2.447 | 2.065 |
| 40    | 100     | 55     | 10.391 | 9.623 | 10.593 | 9.743 | 1.940 | 1.242 |

**TABLE 1.** Experimental results from the present study

**TABLE 2.** ANOVA of Ra using Aluminum electrode and AlCrNi coated electrode

| Source | DF | SS   | MS   | F-Value | P-Value | Contribution % |
|--------|----|------|------|---------|---------|----------------|
| I      | 3  | 24.3974 | 21.8944 | 8.13246 | 161.13 | 95 | 94.5 |
| Vg     | 3  | 0.9366 | 1.0166 | 0.3122 | 0.33887 | 6.19 | 8.25 | 0.029 | 0.015 | 3.64 | 4.4 |
| Ton    | 3  | 0.0426 | 0.0202 | 0.0142 | 0.00672 | 0.28 | 0.16 | 0.837 | 0.917 | 0.16 | 0.09 |
| Error  | 6  | 0.3028 | 0.2464 | 0.05047 | 0.04107 | - | - | - | - | 0.01 | 1.01 |
| Total  | 15 | 25.6794 | 23.1776 | - | - | - | - | - | - |

The variation of current (I), voltage (Vg) and pulse on time (Ton) has affected Ra in EDM with Al electrode and AlCrNi coated electrode has a negligible effect on Ra. Based on the values of the fisher coefficient (F), I is the most significant effect (F is largest), followed by Vg and Ton (F is minimum), respectively. The percentage distribution of the influence of the technological parameters on Ra for both types of electrode materials is quite similar. The percentage distribution of the influence of I is the largest (95% with Al electrode and 94.5% with AlCrNi coated electrode), it’s of Vg (3.65% with Al electrode and 4.4% with AlCrNi coated electrode) and Ton is very small (0.16% with Al electrode and 0.09% with AlCrNi coated electrode).
T_{on} = 1000 \mu s with AlCrNi coated electrode. The higher T_{on} led to an increase in the spark discharge channel. However, the lower peak of the spark would lead to a decrease in R_a.

Figure 3 also shows that R_a in EDM using AlCrNi coated electrode was smaller than with Al electrode. This shows that the machining surface quality has been improved with the coating electrode. The change of I leads to the greatest difference between the R_a of the two electrodes. The reason for the lower R_a in EDM using AlCrNi coated electrode was due to the higher thermal stability of AlCrNi coating material on the surface. This has led to higher erosive resistance of the electrode surface by the heat of the sparks. Hence, the surface layer of the electrode coated with AlCrNi could be changed. The surface hardness of the electrode could also affect the roughness of the machining surface [27]. Since the coating affects the electrical conductivity of spark plasma column, it affects the discharge energy delivered per every pulse. It has considerably affected the surface roughness [27]. The difference between the thermal and electrical conductivity characteristics of the coated electrode material could affect the process of the spark formation and the energy of the generated sparks [22].

3. Effects of Process Parameters on R_a using Linear Regression Model

Many methods have been used to establish regression models in EDM including Taguchi, RSM, ANN, etc. It has been inferred that EDM process requires statistical analysis and optimization to obtain optimal process parameters combinations during the machining process for better surface quality [28]. In this study, Taguchi method was used to determine the regression model of R_a in EDM using Al electrode and AlCrNi coated electrode. The analytical results on the accuracy of the regression model of R_a are shown in Tables 3 and 4. The coefficients R^2 and R^2 (adj) showed the appropriateness of the regression model. Equations (1) and (2) represent a regression model of R_a with Al electrode and AlCrNi coated electrode. The result of the R_a determined by calculation by the regression model is compared with it experimentally (Table 1 and Figure 4). It showed that the experimental and calculated maximum error of R_a was 7.15% with Al electrode and AlCrNi coated electrode. The regression model has the accuracy consistent with the experiment. The modeling has also shown that I and V_g were the main influential parameters on R_a in EDM using Al electrode and AlCrNi coated electrode.

Aluminum= 3.91504+0.10766*I–4.3465e–005*T_{on}+0.04319*V_g     \tag{1}

AlCrNi coating= 3.144+0.104*I–0.000039*T_{on}+0.0443*V_g \tag{2}

3. Determination of the Optimal Technology Parameters

The S/N coefficient is used to determine the optimal technology parameters. The S/N of the R_a is determined by “smaller is better” as shown in Figure 5. It has been shown that the optimum

| Source | DF | SS | MS | F  | P   |
|--------|----|----|----|----|-----|
| Regression | 3  | 22.6813 | 7.5604 | 182.79 | 0.000 |
| Residual Error | 12 | 0.4963 | 0.0414 | - | - |
| Total | 15 | 23.1776 | - | - | - |

R^2 = 97.9%  \text{  \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ R^2(adj) = 97.3%}

| Source | DF | SS | MS | F  | P   |
|--------|----|----|----|----|-----|
| Regression | 3  | 22.6813 | 7.5604 | 182.79 | 0.000 |
| Residual Error | 12 | 0.4963 | 0.0414 | - | - |
| Total | 15 | 23.1776 | - | - | - |

R^2 = 97.9%  \text{  \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ R^2(adj) = 97.3%}
Figure 4. Compare results of experiment and calculated by regression model

Figure 5. Main effects plot for S/N ratio of $R_a$

Figure 6. SEM micro-graphs of machined surface in EDM

Figure 7. Topography of machined surface in EDM

Figure 8. Profile of machined surface in EDM

adhesion debris and micro-cracks on the machined surface in EDM has found with coated electrode as that of Al electrode. The size of particles and the micro-voids on the surface machined with coated electrode was smaller. It could also resulted in the uniform surface topography with lower surface roughness of machined surface with the AlCrNi coated electrode than Al electrode as shown in Figure 7. The size of microscopic cracks on the machined surface with Al electrode was large as shown in Figure 8. This may be due to the improved surface hardness and heat resistance properties of the coating material. It has also resulted in an increase in the erosion resistance of the AlCrNi coated electrode's surface layer with uniformly distributed surface sparks. The electrical and thermal conductivity characteristics of the coating material can facilitate the formation of sparks [24]. Hence the sparks are more uniformly distributed with the smaller beam energy. A partial arcing could be occurred with coated electrode to create tiny micro-voids.

technological parameters in EDM using Al electrode and AlCrNi coated electrode are the identical as $I = 10$ A, $T_{on} = 500 \mu s$ and $V_g = 40$ V. Based on the regression model Equations (1) and (2), the optimal values for both $R_a$ could be determined as follows $R_{a:Al} = 6.698 \mu m$ and $R_{a:AlCrNi} = 5.938 \mu m$. A confirmation experiment at optimum conditions was performed and found as $R_{a:Al} = 6.476 \mu m$ and $R_{a:AlCrNi} = 5.858 \mu m$. It was inferred that the error between the calculated method and experimental error was 7.2% with Al electrode and 4.3% with AlCrNi coated electrode.

3. Surface Quality Analysis at Optimal Conditions

Figure 6 shows that the lower
The discharge gap size was also affected by the surface layer material of the electrode. Hence the size and number of particles adhering to the machining surface could also be improved as the discharge gap size increases. The surface quality after EDM process using AlCrNi coated electrode was observed better than Al electrode.

4. CONCLUSION

In the present study, an investigation was attempted to evaluate $R_s$ of the EDM machined surface with coated and AlCrNi coated Al electrode. Ti-6Al-4V was utilized as specimens using regression model to get optimal technology parameters. From the detailed investigation, the following conclusions were drawn

- The AlCrNi coated tool electrode can produce better surface quality with lower surface roughness, micro cracks and voids than uncoated tool electrode due to its electrical conductivity and melting point.
- The optimal technological parameters with coated and uncoated electrodes were found as $I = 10\, A$, $T_{on} = 500\, \mu s$ and $V_p = 40\, V$ with good accuracy of $4.3\%$.
- $I$ and $V_p$ are the parameters could strongly affect surface quality.
- However more clear research results are needed to comprehensively evaluate the economic and technical efficiency between coated and uncoated electrodes in EDM process.

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Persian Abstract
چکیده
پوشش روی الکترود ابزار در EDM می تواند باعث بهبود بهره وری، مقاومت در برابر سایش الکترود و کیفیت سطح شود. در مطالعه حاضر، زبری سطح ماشینکاری شده EDM با الکترودهای پوشش دار و بدون پوشش بررسی گردید. برای مطالعه آلیاژ تیتانیوم (Ti-6Al-4V) از الکترود Al با روکش Al و AlCrNi استفاده گردید. جریانی (I) و ولتاژی (Vg) به عنوان پارامترهای فنآوری تاکنون به عنوان پارامترهای فنآوری استفاده شده است. از آنجا که I و Vg در برابر مقادیری از میانگین به میزان تأثیر بسیاری است، ضریب تأثیر و نرخ تغییر در پارامترهای فنآوری اختیاری استفاده شده است. در مقاله، تأثیر طبقه بالا کار و تأثیر سایشی الکترود بر کیفیت سطح ایجاد شده مورد بررسی قرار گرفت. الکترودهای پوشش دار به عنوان الکترود بدون پوشش کیفیت سطح بهتری به دست آورد و از این نظر، الکترود پوشش دار به عنوان الکترود مورد استفاده بهتری می‌باشد.

پارامترهای بهینه به عنوان الکترود پوشش دار و الکترود بدون پوشش به عنوان
I = 10 A, Ton = 500 μs و Vg = 40 V برنامه نویسی شد.