Investigation of the $TiO_2/SiC/SiO_2$ Coating Effect On the Wear Rate of Needle Graphite Electrode by using Electrical Discharge Machining

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Abstract: Needle graphite electrodes are one of the main parts used in electric arc furnaces. These electrodes have a significant impact on melt quality and product quality, and their consumption is one of the most important parameters of steel production cost in EAF furnaces. Therefore, reducing the consumption of needle graphite electrodes in these furnaces is very important. The main reasons for continuous use of needle graphite electrodes in arc furnaces are oxidation of the sidewalls and sublimation of their tips, and many solutions have been proposed to reduce them. In the present study, the effect of coating consisting of $TiO_2/SiC/SiO_2$ elements on the wear rate of the needle graphite electrode in the sublimation state is investigated using EDM (Electrical Discharge Machining- Spark device). For this purpose, the effect of voltage, current, pulse on time and pulse off time on the electrode wear rate are investigated and in this regard, Taguchi design method has been used to reduce the number of experiments. Based on the test results, $TiO_2/SiC/SiO_2$ coating reduces the wear rate of the needle graphite electrode due to sublimation.

Keywords: Electric Arc Furnace, Electrode Consumption, Electrical Discharge Machining, Electrode Coating, Needle Graphite Electrode, Oxidation, Sublimation

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1 INTRODUCTION

1.1. Definition and Importance Subject

Electric arc furnaces are used to melt steel. In arc furnaces, electrical energy melts metals by creating an arc between the graphite electrodes and the metal charge, or by creating an arc between the electrodes themselves. Electric arc furnaces are divided into two categories in terms of electric current, direct and alternating. The electric arc furnace used for the purposes of this study is powered by three-phase alternating current [1].

When an electric current is established through an electrode, an electric arc is established between the electrode and the metal, as a result of which it begins to melt. As shown in "Fig. 1" , continuous consumption of graphite electrodes occurs due to both sublimation and oxidation, which typically release carbon monoxide (CO). The CO layer formed around the electrode reduces the effect of oxygen attack on the graphite and anything affecting this protective layer leads to accelerated oxidation losses [3].

There are several coating methods for the graphite such as Slurry-Sintering, Chemical Vapor Reaction, Chemical Vapor Deposition, Pack Cementation and electro phonetic deposition [4-5]. From these procedures, the slurry sintering method is considered the simplest and fastest method with a low process time and the validity of coating things with complicated geometry shapes.

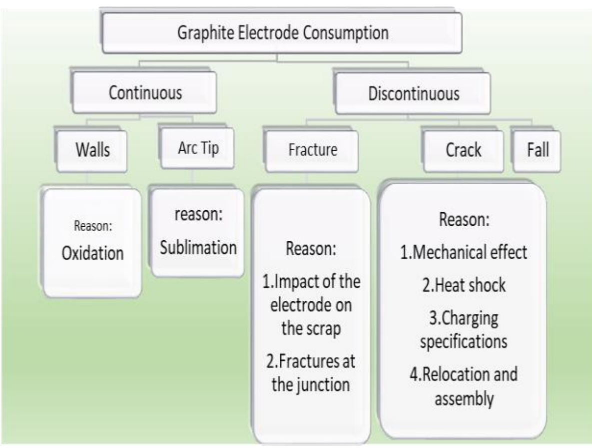

Fig. 1 Graphite electrode consumption diagram [2].

1.2. Background Research

There are many materials (ceramic particles) used until today to coat the surfaces of graphite electrodes. For example, Al_2O_3 [6], Al_2O_3 / SiO_2 [7], SiC [8], BN [9], TiN [10] and SiC / SiO_2 [11]. Also, based on a patent in 1993, the lateral surface of the electrodes Graphite was coated by TiN metal spraying process as a protective layer against ARC, high temperature oxidation and mechanical wear [12]. Schroeder et al. presented a study on the effect of the protective layer on the oxidation of graphite electrodes and investigated the effect of the protective layer coating method such as Chemical Vapor Deposition (CVD) and slippery method [13]. Reference No. [14] Presented a novel process for coating carbonaceous materials in which a layer of aluminum is initially used to coat a mixture of aluminum glue, silicon carbide, TiO_2, and boric acid and the two layers are in a second stage sintered in an induction furnace.

Yang et al. investigated the oxidation and mechanical properties of carbon fibers coated with SiC-ZrO_2-$MoSi_2$/Ni and the results showed that without changing the mechanical properties of carbon fibers, its antioxidant properties increased [15]. In some studies, it has been mentioned that the use of SiC coating on graphite is the most effective method due to the formation of a dense layer of amorphous SiO_2 on the graphite surface [16-17]. Based on thermodynamic analysis, SiC and SiO_2 particles are sufficiently stable at high temperatures [18-19]. In this study, a combination of TiO_2 / SiC / SiO_2 particles was used to fabricate a protective coating layer for graphite electrodes.

In the process of electric discharge machining, Rozenak et al. used a metal-based composite material as a work piece and examined changes in chipping rates and surface roughness by considering various machining parameters [20]. Jeswani et al. investigated the effects of graphite powders added to the dielectric during machining of tool steels. They observed that the addition of graphite powder reduced the discharge voltage and increased the gap. It was also found that the stability of the machining process is improved by increasing the chipping rate [21]. Yan et al. used aluminum and silicon carbide powders to electric discharge machining of the SKD-11 work piece and concluded that the addition of aluminum and silicon carbide powders to the dielectric increased the chip removal rate and increased the surface roughness [22]. Tzang et al. used four types of aluminum, chrom, copper and silicon carbide powders to electrically discharge machining the SKD-11 work piece and showed that the concentration, size, density, electrical resistance and thermal conductivity of the powders have great effects on the discharge machining performance. Their observations show that with increasing the average particle size of the powder, the chipping rate and the wear rate of the electrode increase and at a constant concentration of small powders, the cutting rate increases and the wear rate of the tool decreases [23].

1.3. Illustration of the New Work Compared with Previous Work

According to the mentioned cases, the effect of nanomaterial coating consisting of the TiO_2/SiC/SiO_2 elements on the wear rate of graphite electrode tip has not been investigated so far. in the present study, EDM has been used to investigate the wear rate of graphite electrode tip due to sublimation. in this regard, the effect of voltage, current, pulse on time and pulse off time parameters on the electrode wear rate has been investigated and critical parameters have been identified. Figure 2 shows the EDM machine used to perform the tests.

Fig. 2 Tehran Ekram EDM machine model 204H.

2 THEORY AND TESTING EQUIPMENT

In the designed tests, the Tehran Ekram spark machine, model 204H, made in Iran, was used. One of the most important features of this machine is the ability to change most of the adjustment parameters and high accuracy. In this study, the difference in electrode weight before and after electrical discharge was measured by using a laboratory scale model AND GR-300 with accurately 0.01 gr, and then according to the electrical discharge time and considering the measured density for electrode and using the equation (1), the electrode wear rate was obtained. It should be noted that the discharge time was recorded by a digital timer with an accuracy of 0.01. In this regard, TWR is the electrode wear rate in terms of (mm3 / min), T1, T2 are electrode weight before and after electrical discharge, respectively, ρ_T is electrode density, and t is discharge time(min) [24].

$$TWR = \frac{(T_1 - T_2)}{\rho_T \times t} \times 10^3 \quad (1)$$

Electric discharge method is one of the methods of melting and removing materials from the metal surface, which is used to produce parts with complex, thin and very hard shapes. This process is in fact an electrical discharge process and the source of current generation conducts current to the electrode and work piece. The air gap between the electrode and the work piece is filled with dielectric fluid or air that acts as an insulator. When the voltage reaches a certain level, the dielectric ionizes and creates a plasma arc. Its temperature reaches 14500 ℉ to 22000 ℉ or 8000 ℃ to 12000℃. Due to this heat, the materials are separated from the surface of the work piece in the form of melt or steam, this part is called the light pulse time of the machine [25]. The mechanism of electric discharge machining is shown in "Fig. 3".

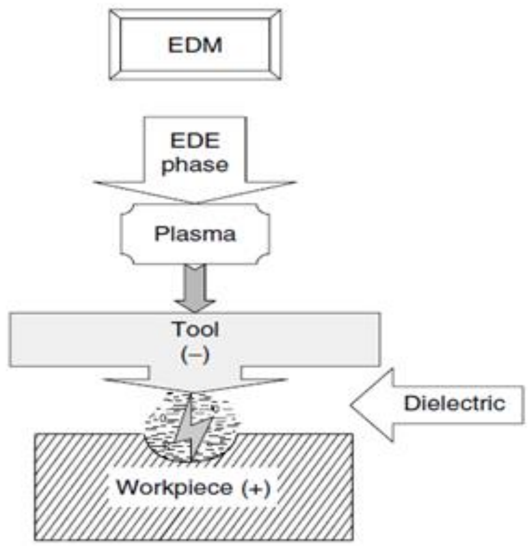

Fig. 3 Electric discharge machining [26].

At the point where the dielectric is broken and ionized, a plasma channel will form and ignite, and thus the melting action takes place. In this place, the concentration or density of energy is about 10^9 to 10^{10} watts per square meter. The rate of temperature increase due to this strong energy density is about 10^{10} ° C [24-26].

To determine the effect of coating on the results of electrode consumption due to sublimation, water (48% by weight of the required slurry) was initially poured into a container before dolapix, and polyvinyl alcohol (as the binder) were added at weight ratios of 2, and 2%, respectively. The mixture was stirred for two hours for complete dissolution of the additives in water before silicon carbide, titanium oxide, and silicon oxide powders (by mesh size 45 nm, 120 nm and 20 nm, respectively) were added to the solution at weight ratios of 20, 20, and 10%, respectively. The final slurry was prepared by stirring the solution thus obtained for one hour using a metal impeller attached to a drill run at 100 rpm. Then, slurry was coated onto graphite electrode specimens previously prepared with a length of 180 mm and a diameter of 16 mm. Figure 4 shows a coated experimental sample before the electric discharge test.

Fig. 4 The experimental specimen coated with mixed $SiC/TiO_2/SiO_2$ particles.

Figure 5 illustrates the morphology of the coated sample. According to “Fig. 5” , the coating adheres well to the electrode surface.

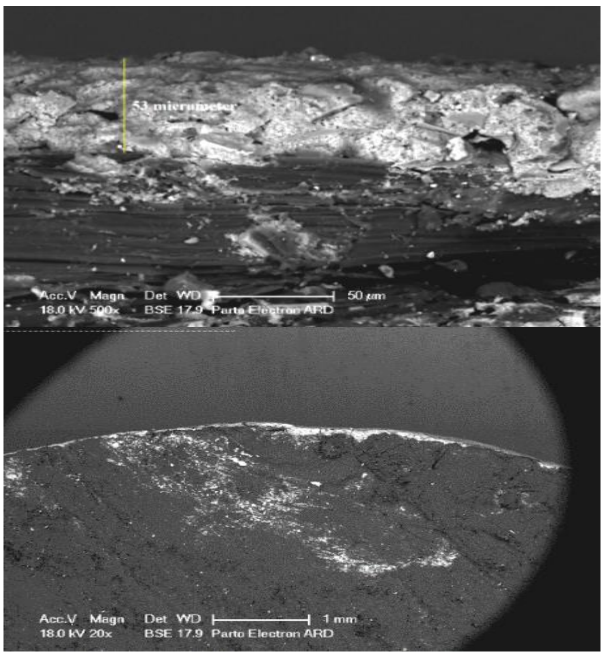

Fig. 5 Surface morphology of the coated sample.

3 RESULTS OF ELECTRICAL DISCHARGE TESTS AND ANALYSIS OF ELECTRODE WEAR DUE TO ELECTRICAL DISCHARGE

In this study, between the available inputs, the effects of four parameters of voltage, current, pulse on time and pulse off time on the electrode wear rate by electric discharge method are investigated. The input parameters of the electrical discharge test and their levels are shown in “Table 1” . After determining the parameters and levels of each, the test method must be determined. According to the number of parameters and selection levels, to complete the tests, 3^4 or in other words 81 tests are needed. Due to the cost and time required to complete the experiments, the Taguchi experimental design method has been used. In order to optimize the number of experiments and increase the generalization of the results to all the studied levels, the orthogonal array L9 and the technique of repetitive levels with repetition of 80 voltage level have been used (EDM machine had only two voltage levels).

Table 1 Input parameters and their levels

Levels	Voltage	Current	Pulse on time	Pulse off time
Level 1	80	10	35	30
Level 2	250	15	50	70
Level 3	80	20	100	200

According to “Table 1” and the results obtained from the output of Minitab software (“Fig. 6”), we will need to perform 9 tests at 3 levels and 4 factors.

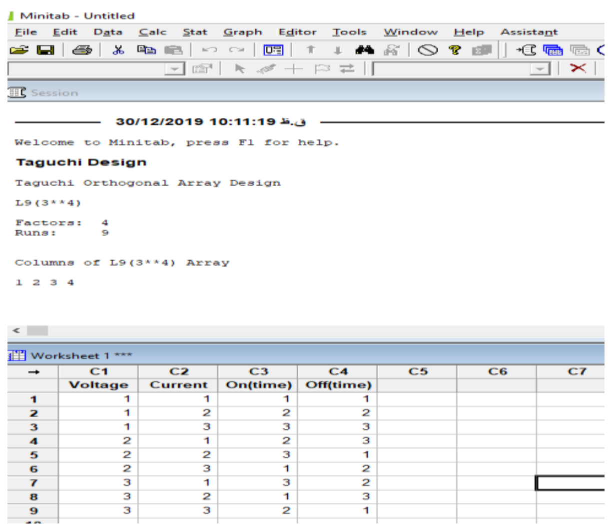

Fig. 6 Create Taguchi Design output of Minitab software.

In the present study, experiments were performed in two stages:

1- Electrical discharge without electrode coating

2- Electrical discharge with electrode coating

First, in both stages, using Taguchi design method, the results were evaluated separately and at the end, in order to investigate the effect of electrode coating on wear, the two modes were compared. The orthogonal array of the Taguchi L9 and the test results according to the table obtained in “Fig. 6” are given in “Table 2” for the uncovered and covered cases.

Table 2 Design of experiments using the L9 array

Design experiments using the L9 array							
Test number	Input parameters				Uncoated electrode output parameters	Coated Electrode output parameters	Percentage reduction of electrode wear rate due to coating
	Voltage	Current	Pulse on time	Pulse off time	Electrode wear rate (cm^3/min)	Electrode wear rate (cm^3/min)	
1	1	1	1	1	0.03	0.02	33.3%
2	1	2	2	2	0.12	0.09	25%
3	1	3	3	3	0.14	0.08	42%
4	2	1	2	3	0.03	0.02	33.3%
5	2	2	3	1	0.25	0.16	36%
6	2	3	1	2	0.05	0.03	40%
7	3	1	3	2	0.03	0.02	33%
8	3	2	1	3	0.07	0.06	14%
9	3	3	2	1	0.24	0.16	33%

As the test results in "Table 2" shows, the $TiO_2/SiC/SiO_2$ coating is effective in reducing the wear rate of the graphite electrode tip up to 42% and thus reducing the electrode consumption due to sublimation. Figures 7 and 8 show the electrical discharge of the graphite electrode in the uncoated and coated state.

Fig. 7 Electrical discharge of the uncoated electrode.

Fig. 8 Electrical discharge of coated electrode.

The outputs of the Analyze Taguchi Design section of the Minitab software are as shown in "Fig. 9 and 10" .

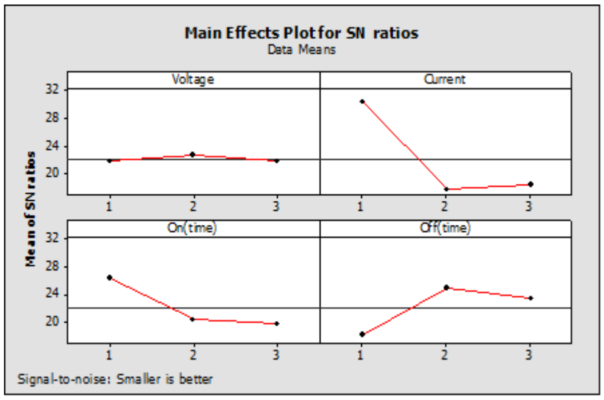

Fig. 9 The effect of input parameters on the electrode wear rate in the uncoated state.

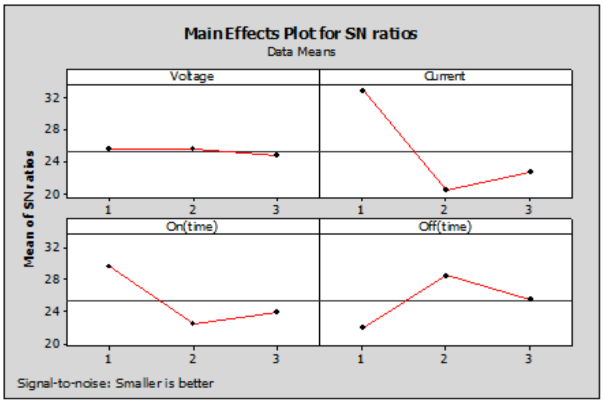

Fig. 10 The effect of input parameters on the electrode wear rate in the coated state.

Figures 9 and 10 show in both coated and uncoated conditions that the wear rate increases with increasing current. The reason for this can be explained by the fact that with increasing current, the spark energy and consequently the surface temperature of the part will increase and the melting and finally the wear of electrode will increase rapidly. By increasing the current, the wear rate of the electrode increases rapidly, while with increasing pulse on time, the electrode wear rate increases more slowly and decreases slightly after level 2.

Basically, the spark energy increases with increasing pulse on time and the current, thus allowing more wear. As the pulse on time increases from a certain value onwards, the plasma channel at the arc location increases and the energy density at the electrical discharge position decreases, which has a negative effect on the electrode wear. In addition, with increasing pulse on time, there is an opportunity for the plasma channel to become wider and as a result, more ions that are positive become more active and attack the negative pole (furnace charge) and more energy is discharged, resulting in more melting and evaporation than the provided charging level by the furnace. As the voltage increases, the electric field in the plasma channel increases, resulting in an increase in the number of electrons and ions. On the other hand, the velocity and energy of the charged particles in the electric field depend on the voltage. Therefore, with increasing voltage, more ions and more energy hit the furnace charge and the melting increases and the electrode wear increases.

4 CONCLUSION

Based on the results obtained, in uncoated and coated state the effects of spark current, pulse on time are known as critical and important effects of the process, respectively. As the current increases, the electrode wear rate increases rapidly, while as the pulse on time increases, the electrode wear rate increases more slowly. By comparing the electrode wear rate before and after coating, it can be stated that in addition to voltage, current and pulse on time settings, electrode coating also has positive effects on reducing the electrode wear rate. According to nine experiments performed at different levels of voltage, current, pulse on time and pulse off time parameters, the results showed that $TiO_2/SiC/SiO_2$ coating can be effective in reducing electrode wear rate up to 42%. Therefore, use of $TiO_2/SiC/SiO_2$ coatings in steel making plants that use electric arc furnaces is recommended.

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