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RESEARCH ON WEAR RESISTANCE OF CARBONIZED 45 STEEL BY ELECTRO-SPARK DEPOSITION TECHNOLOGY

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Electro-spark deposition (ESD) is a green manufacturing method which is more energy-efficient than traditional heat treatment methods and has minimal environmental pollution. ESD enables rapid carburization of metal surfaces by the graphite electrode. Thus, the wear resistance property of the metal surface is improved. ESD can carburize the surface of large steel structure parts in agriculture, improving wear resistance and service life. The traditional carburizing process costs much money and is difficult to achieve. ESD carburizing can save much money and even carburize the partial surface of the part. The traditional carburizing process cannot achieve these. This research employed rapid ESD equipment with rotary electrodes for the surface carburization of No.45 steel. The experiments used the Taguchi orthogonal array (OA) factorial design method. The four critical factors of the ESD process, such as energy, duty cycle, voltage and frequency, were tested. Four parameters and four levels were used to perform sixteen groups of carburizing experiments. The free-state graphite powder was removed from the surface of the deposited samples. The deposited surfaces were analyzed by X-ray diffraction (XRD). According to the diffraction pattern, the composition of the material was compared. It was found that wear-resistant Fe_3C and modified sintered graphite. The linear reciprocating dry friction experiments at room temperature were carried out with a 6mm CrO_2 friction ball under 15N pressure. The ultra-deep field microscope was used to examine the experimental surfaces, and the characterization parameters were based on the abrasion marks. The parameters were characterized by an ultra-deep field microscope and analyzed according to the abrasion marks. The abrasion marks can help to obtain three feasible deposition process solutions. Finally, the extreme value design of Taguchi OA was carried out on the width of abrasion marks. The optimized process solution was obtained and verified by experiments. In this article, abrasion mark method can better characterize the wear resistance of materials than other methods. The abrasion marks method was more convenient when the interface between the coating and the substrate (such as carburized materials)was not obvious. The process scheme can help enterprises solve the carburizing process of large carbon steel parts.

Key words: *Electro-spark deposition, Carburization, Taguchi method, Wear resistance, Abrasion marks.*

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1 Introduction

The electro-spark deposition is used as a traditional surface enhancement method. Lazarenko B. and Lazarenko N. initiated the processing theory(Stavitskii, 2010), which is now widely used in surface machining processes. Since metallurgical bonding can be achieved on metal surfaces through electro-spark discharge, ESD can harden metal surfaces and improve their wear resistance and fatigue strength. It is widely used in the generation of surface coatings on metals. The ESD can achieve strengthening on the metal surface, such as carburization(VB Tarelnyk et al., 2018), nitriding(Viacheslav Tarelnyk et al., 2022), sulphurisation(Viacheslav Tarelnyk et al., 2017), nitrocarburisation(Gaponova et al., 2022) and aluminized surface (Kirik et al., 2018).

Viacheslav investigated the carbonization process using discharge energy(VB Tarelnyk et al., 2018) and graphite powder (VB Tarelnyk et al., 2022). Karavaev studied surface wear resistance with the current and the number of machining cycles in ESD (Karavaev et al., 2019). Shevchenko analyzed the ultrasound method in the process of carburizing(Shevchenko, 2020).

The 45 steel had low cost and good overall mechanical properties but had poor wear resistance (Chen et al., 2013). The carburizing process was carried out by adding carbon to the surface layer of the metal, which formed a high-strength carbide(Dai et al., 2022). The carburizing furnace was used by adding gas, liquid, or solid in the traditional carburizing process(Nakayama, 1992). The metal was heated to a certain temperature, maintained a particular time to achieve, and carburized(Edenhofer et al., 2015). For large equipment, carburizing required special large equipment and high costs. For some specific structures, it was even hard to carburize. ESD carburizing can be carried out on the surface of large machinery and equipment outdoors without the special carburizing furnace. The carburizing process was studied using graphite electrodes to improve the wear resistance of 45 steel(Padgurskas et al., 2017). It is particularly advantageous for agricultural machinery, pumps, and mechanical tools. These machines are often made from 45 steel, which is a good value for money and is used as the base material.

2 Materials and Methods

2.1 Material Process and Deposition Parameters

First, No. 45 steel with a size of 25*30mm and 2mm thick was used as a sample. Then, the surface was sanded separately using 600-grit sandpaper to remove the oxidized layer and impurities. The surface was cleaned with 99% ethanol. Finally, a high-speed ESD repair machine(fig.1 Huimite HMT9500, China) was used for carburizing the 45 steel surface. The 3mm diameter graphite rod was used as an electrode, and Argon was used as a shielding gas. A 4-factor and 4-level test was carried out using a Taguchi OA factorial design (Weiwei et al., 2007). The process parameters are shown in Table 1.

Fig. 1- The high-speed ESD repair machine (HMT9500)

Table 1

The ESD carburizing process parameters

No.	Efficiency(%) A	Voltage(V) B	Current Frequency(Hz) C	Time(s) D
1	20(1)	25(1)	100(1)	120(1)
2	30(2)	35(2)	180(2)	240(2)
3	40(3)	45(3)	260(3)	360(3)
4	50(4)	55(4)	340(4)	480(4)

( )-Level values in brackets

2.2 Materials Testing methods

Graphite powder was wiped from the machined surface with a brush. The composition of the deposited surface was analyzed by the X-ray diffraction(XRD) method (Bruker D8, Germany). The experiments were carried out using a linear reciprocating friction wear machine (Huaxin MWF-500, China). The sample was fixed through a special fixture. A 6mm diameter friction ball (ZrO2, G10 accuracy) was used for the surface abrasion test, as shown in Fig. 2. The electric motor rotated at 100r/min, and the reciprocating distance was 6mm. Thus, the motor performs two times movements per 1 cycle. The experimental time was 15 min for the reciprocal dry friction experiment. The temperature of the experimental environment was 25ºC, and the humidity was 53%. Abrasion debris was produced on the surface of the friction samples. The surface powder was removed with a brush. The surface was scratched with alcohol and dried naturally. Then, the samples were weighed on a balance (Sartorius BSA224S-CW, China). Finally, the abrasions were measured with a microscope (Leica DVM6, Germany).

$$V_W \approx L \times \left(2L_{AH} * L_{BC} / 3 + 8L_{AH}^3 / 15L_{BC} \right) \quad (1)$$

$$L_{AH} = R - \sqrt{R^2 - \left(L_{BC} / 2 \right)^2} \quad (2)$$

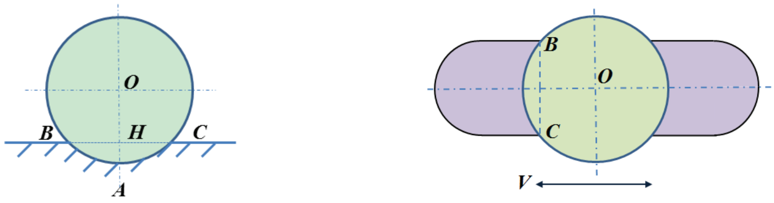
In equation 1: V_W -Wear volume of the sample, *mm³*. L -Length of abrasion, *mm*. L_{AH} -Depth of abrasion, *mm*. L_{BC} -Width of abrasion, *mm*. In equation 2: R -Radius of the friction ball, *mm*. Three abrasion mark experiments were carried out, and the relevant parameters were measured.

3 Results and Discussion

3.1 Abrasion morphology of the carbonized experimental samples and non-carbonized samples

Carburization deposition of 45 surfaces was carried out according to the experimental parameters in Table 1. Wear resistance can be analyzed based on the quality of the deposition (Mikhailyuk et al., 2010). Because the carburized surface had graphite powder, this paper used abrasion marks for the analysis (Zhu et al., 2019).

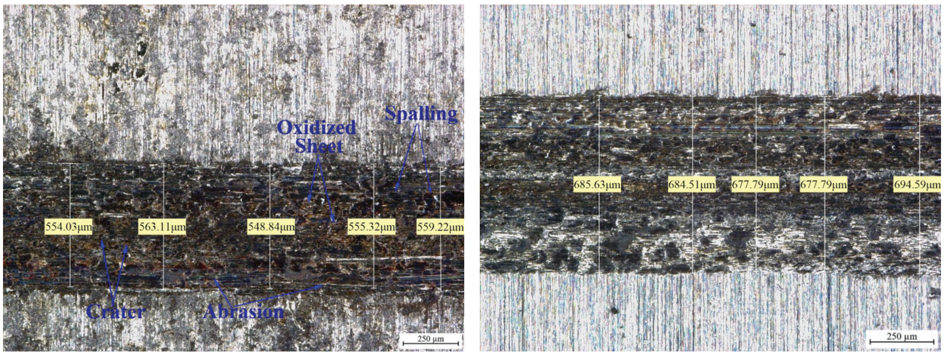
The wear resistance of the metal surfaces was tested using the linear reciprocal friction and wear machine. There were free-form graphite powder and sintered-form graphite powder on the carburized surface. Then, free-form graphite powder on the surface was gently scrubbed with a soft brush. The machine adopted ZrO2 rubbing ball as counter-abrasive material on a steady pressure of 15 N. Each friction test was carried out three times. The width of the middle part of the abrasion was measured five times. The maximum value, minimum value, and middle values were measured (Fig. 3). At the edges of the abrasions, there were clear spalled areas of the material which were not smooth (Fig. 3a). The distinctive scratches appeared at the upper edge of the abrasion mark. When carbide powder with hard phases on the underside was broken off by the force of the friction ball, it moved toward the outside of the scratch. The abrasions gradually grew in size under the reciprocal rubbing process. The apparent oxidized sheet



a) b)

Fig. 2-Schematic diagram of the friction ball: a)parameter diagram of abrasion marks; b) movement diagram of the friction ball

appeared at the bottom of the abrasion, which indicated that the friction force increased during the sliding process. These led to increased surface roughness and plastic deformation of the micro-protrusions. It caused an increase in local temperature and accelerated oxidation of the surface. There were tiny scratches at the bottom of the abrasion, hard spot burnishing on the bottom, and craters on the surface. Through the experimental comparison group, it was found that the abrasion width was smaller than that of the sample without carbonization (Fig. 3b). Due to the generation of hard particles on the worn surface, the increase in surface friction led to the appearance of an oxidized layer.



a) b)

Fig. 3-The 500X morphology of abrasion: a) Abrasion in carbonized materials; b) Abrasion in uncarbonized materials.

3.2 Results of orthogonal carbonization experiments

The deposition experiments were carried out by 4 level 4 factor factorial design. Four factors included efficiency (duty cycle), discharge voltage, current frequency, and time(Xiang et al., 2017). Moreover, the average values and the average variances of the abrasion width were plotted, respectively. The samples without surface carbonization were also analyzed for comparison. It can be seen from Table 2 that the average value of sample 6 was the smallest, and the abrasion width of samples 3, 7, and 15 were smaller (Fig. 4). In the three samples, the variance of sample 15 was better than that of sample 3 and sample 7(Fig. 5). In contrast, sample 9 had the widest wear masks. Corresponding parameters such as efficiency (duty cycle), discharge voltage, current frequency, and time were all small. The carburizing effect was not good, and the wear resistance was poor.

Due to the accumulation effect of continuous pulses of current, sample 11 had a significan duty cycle value and voltage value, but the electrode graphite was significantly ablated at the head of the electrode, and the surface deposited was not the highest value for wear resistance. It showed that the abrasion width was smaller, and the wear resistance was better. The variance was also small, indicating that the surface uniformity was good. The average values and the average variances of the abrasion width should be considered comprehensively.

According to the comparison group, it was found that uncarbonized samples had a larger width of abrasion marks than the carburized ones (Fig. 4b). Their mean variances were smaller than that of the carburized group, which indicated that the material properties were close (Fig. 5b). However, carburized samples had been altered material properties due to the different carburizing process parameters. Because the hard phase was unevenly formed on the surface of the carburized sample, it would cause a sizeable average variance.

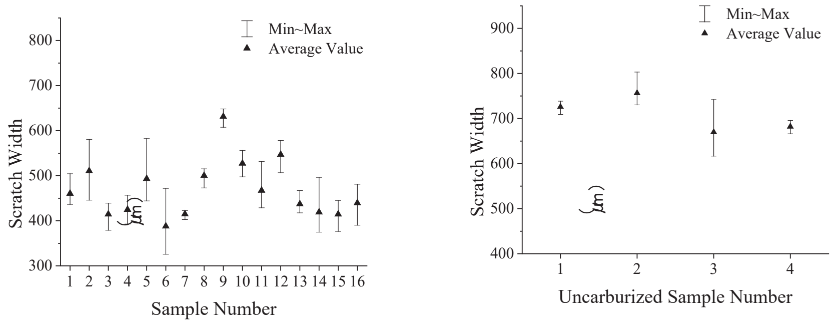
3.3 XRD analysis of carbonized surface

XRD analyses were carried out on the deposited samples. The surface of 45 steel was found to be mainly graphite and Fe_3C. And Fe_3C generated on the surface

Table 2

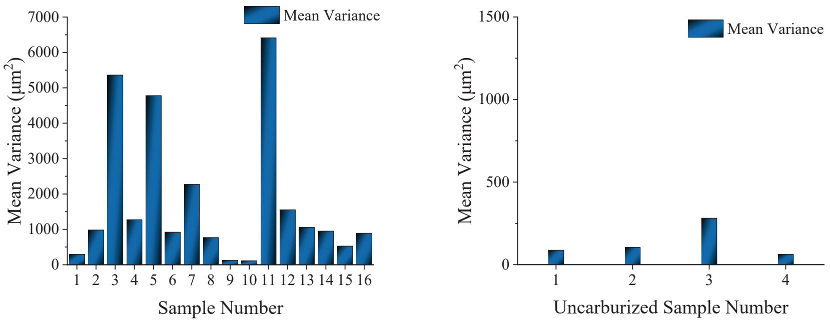
The ESD carburizing process parameters

No.	Factor1	Factor2	Factor3	Factor4	Abrasion Width	
	A	B	C	D	Average Value ,(μm)	Average Variance,(μm²)
	Efficiency, (%)	Volt, (V)	Current frequency, (Hz)	Time, (s)		
1	20	45	260	360	460.38	290.58
2	30	25	180	360	510.61	982.07
3	40	55	180	120	414.52	5360.59
4	40	35	340	360	424.84	1272.93
5	50	55	100	360	493.33	4780.89
6	20	55	340	480	387.93	921.12
7	50	35	260	120	414.88	2273.91
8	30	35	100	480	500.09	769.31
9	20	25	100	120	631.11	126.59
10	20	35	180	240	527.41	113.30
11	50	45	180	480	467.29	6410.23
12	30	55	260	240	546.79	1552.33
13	40	25	260	480	437.15	1053.56
14	50	25	340	240	419.06	949.52
15	30	45	340	120	414.47	526.93
16	40	45	100	240	439.39	891.23



a) b)

Fig. 4-The Average Value of Abrasion Width: a) Experimental groups of Taguchi OA; b) Uncarbonized experimental groups



a) b)

Fig. 5-The Variance of Abrasion Width: a) Experimental groups of Taguchi OA; b) Uncarbonized experimental groups

of 45 steel (Krishnia et al., 2016)was the hard phase that increased wear resistance(BALTUŠNIKAS et al., 2006). In the friction wear test, the surface produced a mixture of Fe_3C hard particles and graphite, which weakened the lubrication effect of graphite in dry friction. Ferrum was not detected on the surface(Fig. 6), indicating that the surface was completely carbonized.

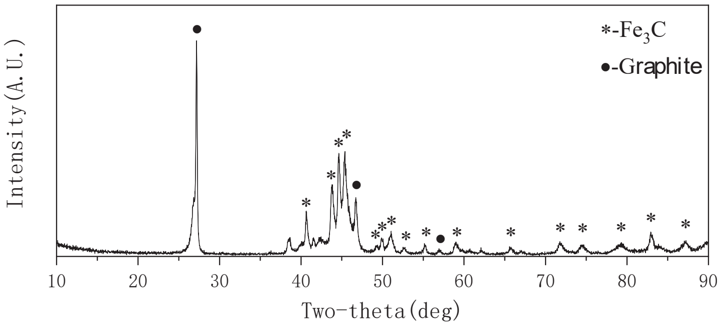


Fig.6- XRD patterns of the carbonized surface on 45 steel

3.4 Data Analysis of Orthogonal Experiment

Orthogonal experimental calculation of deposition data was carried out on 4-factors and 4-levels by Taguchi theory. As the value of the abrasion width was smaller, the wear resistance was better (Reséndiz-Calderón et al., 2020). It was selected that the minimum value corresponded to the four factors. It can be seen from Table 3 that a smaller extreme R meant a more significant factor. According to extreme R, the effect on wear resistance was found to be time D > efficiency A> frequency C > voltage B.

It was found that the longer time did not mean better deposition but that there were essential links in the four factors. In the experiments, the electrode temperature rose too quickly when the duty cycle, voltage, and frequency were large. The graphite ablation was serious. So the deposition process could not obtain optimal results (Fig.7). Therefore, reasonable process parameters were the key to the carburized process.

In Table 3, A4B2C1D3 was chosen as optimal parameters. Among the experimental samples, A1B4C1D3(sample 6),

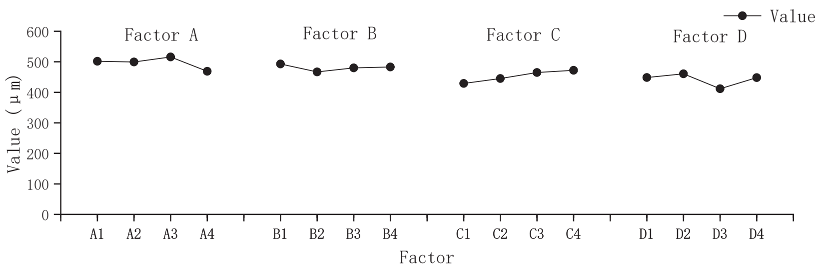


Fig. 7-Variation trend of the width of the abrasion marks with process parameters

A3B4C4D1 (sample 15), and A4B2C3D1(sample 7) have better wear resistance and surface uniformity. They can also be used as an alternative in industrial applications.

3.5 Surface abrasion morphology and parameters of the optimal process

The optimal process parameters were selected for deposition (Table 4). Fig. 8 shows finer abrasion marks. It indicated that the material had better wear resistance. Although the solidified graphite was deposited on the surface, it had a small brown oxidized layer in the middle of the abrasion marks on the surface. The mass of wear powder was smaller, and the abrasion width was narrower. So the surface wear resistance was better. The average abrasion width of sample 2 (Fig. 4b) was 756.441 μm. According to equation 2, the depth of abrasion was 23.937 μm, which was substituted into equation 1 to obtain the volume of 85.484 x 10^{-6} mm^3. The density of Ferrum was 7.87g/cm3, and the wear quality was calculated as 6.73×10^{-4}g.

Table 4

Optimal process parameters for surface carbonization deposition on 45 steel

A4	B2	C1	D3
Efficiency, (%)	Voltage, (V)	Current frequency, (Hz)	Work Time, (s)
50	35	180	360

Similarly, in the optimal process, the average value of the abrasion width was 268.206μm, and the depth of abrasion was 2.999 μm according to Equation 2, which was substituted into Equation 1 to give a volume of 3.217 × $10^{-6}$$cm^3$. Because the density of fe3c was 7.694 g/cm3 (Haynes et al., 2016),

Table 3

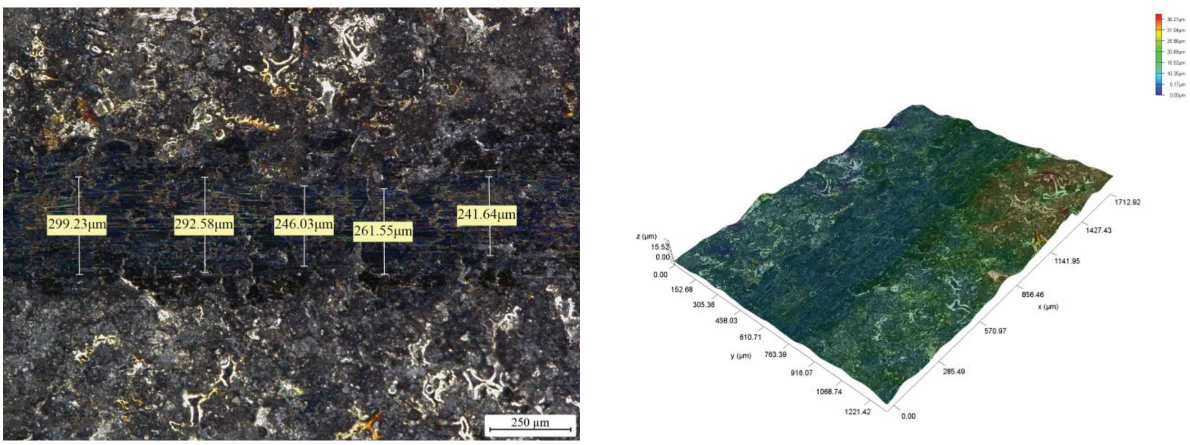
Orthogonal experimental calculation

	A	B	C	D	Value
1	1	3	3	3	460.38
2	2	1	2	3	510.61
3	3	4	2	1	414.52
4	3	2	4	3	424.84
5	4	4	1	3	493.33
6	1	4	4	4	387.93
7	4	2	3	1	414.88
8	2	2	1	4	500.09
9	1	1	1	1	631.11
10	1	2	2	2	527.41
11	4	3	2	4	467.29
12	2	4	3	2	546.79
13	3	1	3	4	437.15
14	4	1	4	2	419.06
15	2	3	4	1	414.47
16	3	3	1	2	439.39
k1j	501.71	492.99	428.98	448.64	
k2j	499.48	466.81	445.38	460.64	
k3j	515.98	479.96	464.80	411.58	
k4j	468.75	483.16	472.29	448.12	
QJ	1985.92	1922.92	1811.45	1768.97	
MIN	468.75	466.81	428.98	411.58	
R(MAX-MIN)	47.24	26.19	43.32	49.07	
OPTIMAL VALUE	A4	B2	C1	D3	

the abrasion mass was 2.47 × 10^{-5}g. The balance is difficult to guarantee the measurement accuracy of the quality. Due to the rough texture of the abrasive surface (Fig. 8b) (Zhu et al., 2019), the actual wear quality should be smaller than the theoretical calculation. The wear resistance was compared by the abrasion width, and the width of the wear scar has excellent accuracy compared to the quality on the carburized surface of 45 steel. Optimization of the carburizing parameters results in better wear resistance.

4 Conclusions

Metal surfaces can be easily carbonized by the graphite electrode. On the basis of the obtained test results, ESD can increase the wear resistance of the material surface. Process parameters are essential in electro-spark deposition.



a) **b)**

Fig. 8-Surface abrasion morphology of the optimal process:
a) 2D Shape; b) 3D super depth of field morphology.

1) It was used to comprehensively evaluate the wear resistance with better results that average width and average variance of abrasion marks when the graphite powder and the grinding dust were small in mass. This article showed the abrasion marks method was easier than other method in the carburized materials.

2) It was used Taguchi's factorial method and calculation to find out the optimal process to guide graphite deposition. The deposition parameter values were larger, but the abrasion width was not necessarily smaller, and the wear resistance was not necessarily the best. An optimal process parameter and three industrial alternatives were found by experimental design.

3) Free graphite powder and sintered graphite powder are produced on the carbonized surface. If the wear resistance is analyzed according to the quality of the deposition, graphite powder on the surface is susceptible to treatment methods and humidity. These can then cause significant errors in the statistical results. Therefore, the abrasion marks method can accurately evaluate wear resistance. It can be used in powder composites.

4) The graphite powder on the surface reduced friction in the early stages of friction, but it had a limited effect with the hard abrasive powder on the reduction of friction. There even was an oxidized layer on the deposition of the surface.

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Дослідження стійкості до зносу карбонізованої 45 сталі за допомогою технології осадження електропроводу

Електроіскрове осадження (ЕІО) - це екологічно чистий метод виробництва, який є більш енергоефективним, ніж традиційні методи термічної обробки, і має мінімальне забруднення навколишнього середовища. ЕІО забезпечує швидке навуглецювання металевих поверхонь графітовим електродом. Таким чином, покращується зносостійкість металевої поверхні. ЕІО може зневуглецювати поверхню великих сталевих конструкцій у сільському господарстві, покращуючи зносостійкість і термін служби. Традиційний процес цементації коштує багато грошей і його важко досягти. Електрохімічне зневуглецювання може заощадити багато грошей і навіть зневуглецювати часткову поверхню деталі. Традиційний процес цементації не може цього досягти. У цьому дослідженні було використано обладнання для швидкого електроерозійного зневуглецювання з обертовими електродами для поверхневого зневуглецювання сталі №45. В експериментах використовувався метод факторного планування ортогональних матриць Тагуті. Було протестовано чотири критичні фактори процесу електроерозійної обробки, такі як енергія, робочий цикл, напруга і частота. Чотири параметри і чотири рівні були використані для проведення шістнадцяти груп експериментів з цементації. Порошок графіту у вільному стані був видалений з поверхні осаджених зразків. Осаджені поверхні були проаналізовані методом рентгенівської дифракції (XRD). За дифракційною картиною порівнювали склад матеріалу. Було виявлено, що зносостійкий Fe_3C і модифікований спечений графіт. Експерименти з лінійного зворотно-поступального сухого тертя при кімнатній температурі проводили з 6-міліметровим фрикційним шариком CrO_2 під тиском 15 Н. Для дослідження експериментальних поверхонь використовували надглибокий польовий мікроскоп, а параметри характеризації базувалися на слідах стирання. Параметри були охарактеризовані за допомогою надглибокого польового мікроскопа та проаналізовані відповідно до слідів стирання. Сліди стирання можуть допомогти отримати три можливих технологічних рішення для осадження. Нарешті, було проведено розрахунок екстремальних значень Taguchi OA по ширині слідів стирання. Оптимізоване технологічне рішення було отримано і перевірено експериментально. У цій статті показано, що метод слідів стирання може краще характеризувати зносостійкість матеріалів, ніж інші методи. Метод слідів стирання виявився більш зручним, коли межа розділу між покриттям і підкладкою (наприклад, обвуглені матеріали) не була очевидною. Технологічна схема може допомогти підприємствам вирішити процес карбюризації великих деталей з вуглецевої сталі.

***Ключові слова:** Електроіскрове осадження, цементація, метод Тагуті, зносостійкість, сліди стирання.*