Research Article

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Wear and corrosion behavior of TiC and WC coatings deposited on high-speed steels by electro-spark deposition

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Abstract: Electro-spark deposition (ESD) is one of the most effective methods for improving the surfaces of metallic materials by applying ceramic-based cermet coatings. In this study, TiC and WC coatings were deposited on the surface of AISI M2 high-speed steel using the ESD method. Subsequently, the coated surfaces were examined through microstructure, phase structure, microhardness, friction, wear, and electrochemical corrosion tests, and compared with untreated AISI M2 steel. The TiC and WC phase coatings obtained with ESD resulted in a significant improvement, with hardness levels exceeding four times that of AISI M2 steel, leading to reduced wear volume losses and friction coefficients. Furthermore, the cermet coatings formed on the surface exhibited 2–3 times improvement in corrosion resistance due to their lower conductivity. This study demonstrates that WC coatings may offer a more effective solution for enhancing the wear resistance of AISI M2 steel, while TiC coatings could be more effective in improving corrosion resistance.

Keywords: electro-spark deposition, TiC, WC, wear, electrochemical corrosion

1 Introduction

Due to their superior performance, high-speed steels (HSSs) are among the most important steels used in the automotive industry, especially in the engines and powertrains of vehicles. HSSs are materials that can retain their metal removal ability even at high cutting speeds and their hardness to a large extent and for a long time even at high temperatures, with different amounts of alloy element reinforcement. They are widely preferred in the tool industry due to their high toughness, high strength, and low cost [1]. However, due to their brittleness, they partially limit their use in studies involving high impact force and fatigue [2].

Corrosion and wear damage to materials first start from the surface [3]. In order to minimize these damages, alloying with different elements or heat treatment can be applied. However, due to the high cost of these processes, using regional coating methods with more durable materials with different contents is more economical solutions to increase the service life of the tools. Although many coating techniques are used today, Electro-spark deposition (ESD) is used extensively in coating applications with the developing technology, as well as being used as a micro welding in the repair sector.

The formation of a discontinuous, rough structure on the material surface in ESD coating, the uncontrollable coating layer thickness [4], and the formation of cracks due to the different thermal expansion properties of the electrode-coated material restrict its use, especially in decorative areas. On the other hand, the fact that the application can be carried out on-site, low energy consumption [5], not causing thermal deterioration due to low heat input [6], and not causing any change in the metallurgical properties of the coated material [7] are the most important reasons for preference.

ESD is a low-heat input pulsed micro-bonding process that uses high-current, short-duration electrical pulses to bond an electrode material to a metallic substrate. Although this process is basically similar to pulsed micro-arc welding, it is different because short electrical pulses are used [5,8]. The system consists of a consumable electrode, an electrode holder applicator (rotary or fixed depending on preference), and a capacitor power supply. In the system, the electrode is the anode and the workpiece to be coated is the cathode. The coating process is carried out by the electric current generated by the discharge of the capacitor from the anode to the cathode, and the droplets broken off from the electrode are
sprayed towards the workpiece and adhered by mass transfer. Short-term high-current, low-voltage electrical pulses are used [9]. Due to high cooling rates of $10^5$–$10^6$°C/s during ESD, very rapid solidification sometimes causes the material to form a nanocrystalline or amorphous structure, providing benefits in terms of increased hardness, tribological properties, and corrosion resistance [10,11].

In this study, the surface of AISI M2 steel, one of the HSSs, was coated with the ESD technique using TiC and WC electrodes. The coating layer was examined microstructurally and the effect of the coating on the material properties was investigated in detail by wear and electrochemical corrosion tests.

2 Experimental studies

AISI M2 steel, whose chemical composition is given in Table 1, was used as the substrate material to be coated.

AISI M2 steel of Ø16 × 10 mm size, sanded up to 1,200 grit, was used for the coating for metallographic examinations after coating. The samples were cut perpendicular to the coating layer, sanded up to 1,200 grit, polished with 1 µm alumina paste, and etched with 3% nital. Huys brand 630 model ESD device was used as the coating device. For all coatings, the frequency was 160 Hz, the voltage was 60 V, the capacitance was 170 µF, the electrode rotation speed was 150 rpm, and the substrate material rotation speed was 150 rpm. The graphical representation of the system is given in Figure 1.

Coating layer pictures, surface pictures after corrosion tests, layer thickness measurements, and elemental analyzes (EDX) were made on a LEO 1430 VP SEM microscope. Layer thickness hardness was measured on a SHIMADZU HMV-2 model microhardness device at 50 g load, and the average of five measurements was taken. X-ray diffraction of the phases formed on the surface by coating was determined on the SHUMADZU XRD-6000 device. The wear test was carried out in a dry environment, at room temperature, in a ball-on-disc system, using a Ø8 mm WC-Co ball, at a wear speed of 0.2 m/s, using a load of 5 N and a distance of 250 m. Wear areas were measured from the cross-sectional area of the wear on the NANOVEA brand Tribotechnic Rugosimeter device. Wear rates were calculated by multiplying by the track width and according to the formula in equation (1).

$$\text{Wear rate (mm}^2\text{/Nm)} = \frac{\text{worn volume (mm}^3\text{)}}{\text{load (N)} \times \text{distance (m)}}.$$  (1)

Electrochemical corrosion (potentiodynamic polarization) tests were performed on the Gamry Reference 600 Potentiostat/Galvanostat device using the Echem Analyst Software program. The tests were performed in a three-electrode system, at room temperature, in 3.5% NaCl liquid solution, and a saturated calomel electrode was used as a reference. Tafel curves were determined so that the potential range per Ecorr was +250 mV and the scanning rate was 1 mV s$^{-1}$. Corrosion rates were determined based on Faraday’s principle. Polarization resistance (Rp) was also calculated from the polarization resistance curves (LPR). Using ASTM G102-89 standards as reference, corrosion rate (MPT), polarization resistance ( Rp), electrochemical corrosion rates (µA × cm$^{-2}$) were calculated.

3 Results and discussion

3.1 Microstructure, hardness, and phase analysis

In Figure 2, the microstructure images of the coating layer taken from the cross-section of (a) TiC and (b) WC coating of AISI M2 steel with ESD are given together with their elemental analysis (EDX).

When Figure 2 is examined, the alloying zones become clearly evident in both coating types. There are small pores

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mo</th>
<th>Cr</th>
<th>W</th>
<th>V</th>
<th>Co</th>
<th>Si</th>
<th>Ni</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI M2</td>
<td>0.97</td>
<td>4.92</td>
<td>3.76</td>
<td>6.99</td>
<td>1.74</td>
<td>0.76</td>
<td>0.23</td>
<td>0.34</td>
<td>0.17</td>
<td>0.01</td>
<td>0.03</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of AISI M2 steel
and cracks in the matrix/coating layer transition and coating layers. There are many reasons for the formation of these defects. One of these is that while the coated metal has good electrical conductivity, the electrical conductivity of the material used as the coating electrode is relatively poor due to its ceramic basis. Due to the low electrical conduction coefficient of the electrode, its melting ability decreases and may make alloying difficult [12]. On the other hand, microarcs form quickly, and micro distortions occur during solidification due to differences in thermal expansion coefficients of the coated material and the electrode [4,7,13]. It is known that ESD coating is made in overlapping passes, and it has been noted that the most efficient coating is obtained in coatings applied up to three passes [14,15]. The ESD process is a method of instantaneous heating and rapid cooling. Another reason is that if the liquid electrode material passing to the substrate surface is not completely solidified, the next pulse discharge will occur. This increases thermal stress [16]. Since the defects are mainly in the matrix/coating transition zone, it is evident that their formation is more intense in the first pass of the coating. Because in this region, there is the highest difference in thermal expansion coefficient and electrical conductivity coefficient. As we move to the upper passes, coefficient differences become more

Figure 2: Coating layer and EDX images of (a) TiC and (b) WC-coated AISI M2 steel.

Table 2: Coating values of uncoated, and TiC- and WC-coated AISI M2

<table>
<thead>
<tr>
<th>Values</th>
<th>Uncoated AISI M2</th>
<th>TiC-coated sample</th>
<th>WC-coated sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating layer (µm)</td>
<td>—</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>Hardness (HV₀.₀₅)</td>
<td>450</td>
<td>1,558</td>
<td>1,322</td>
</tr>
</tbody>
</table>
minor, and errors tend to decrease since the lower coating passes consist of electrodes alloyed with the matrix material. In ESD coating of AISI M2 steel with TiC and WC, the coating layer thickness and hardness values are given in Table 2.

According to Table 2, the layer thickness was measured as 28 µm in the coating made with TiC and 24 µm in the coating made with WC. When the hardness change of the layer with the coating is examined, the surface hardness of AISI M2 steel increases with coating, as in other coating methods [17]. While the hardness of AISI M2 steel is 450 HV<sub>0.05</sub>, the surface hardness was measured as 1,322 HV<sub>0.05</sub> in coating with WC and 1,558 HV<sub>0.05</sub> in coating with TiC. There are many parameters that affect surface hardness in ESD coating. Since the composite coated electrodes (WC and TiC) used are ceramic-based, it is an expected result that the surface hardness increases with the coating. On the other hand, the alloying of the elements in the electrode and the material to be coated also has a positive effect on the coating hardness. Because structural hardening, which occurs due to the precipitation or dissolution of alloy components in solid solutions, probably causes an increase in hardness [13].

During the coating, the particles break off from the electrode and adhere/alloy to the material. With rapid cooling during this process, metastable formations occur during solidification, strengthening the solid solution and increasing the hardness [18].

Figure 3 shows the XRD pattern of AISI M2 steel coated with TiC and WC electrodes using the ESD technique.

When Figure 3 is examined, in the coating made with WC electrode, there are peaks of the Fe<sub>3</sub>W<sub>3</sub>C phase along with the WC phase on the surface morphology, and in the coating made with TiC electrode, there are peaks of the TiC phase and Ti<sub>8</sub>C<sub>5</sub> phase. The detection of peaks belonging to different carbide compounds in the coating indicates that the particles (W/Ti and C) broken off from the electrode during the coating adhere to the material surface and begin to spread by forming an alloy with the elements contained in the coated substrate material [19,20]. These phases, which have a more stable structure, increase surface hardness, wear, and corrosion resistance.

In the prominent peaks of both coatings, there is the M<sub>23</sub>C<sub>6</sub> (M = Cr, Fe) phase due to the alloying elements in the chemical composition of AISI M2 steel, and in the other peaks, there are peaks belonging to the M<sub>7</sub>C<sub>3</sub> phase. This situation can generally be explained in two ways. The electrode material and the coated material form an alloy. On the other hand, the ESD coating process is done manually. In coatings made in this way, the surface morphology is very difficult to control and does not show homogeneity throughout the layer. It has been reported in previous studies that when the number of coatings exceeds three, mass transfer and coating layers do not increase. Therefore, in ESD coatings, the XRD pattern can also be affected by

![Figure 3: XRD pattern of TiC and WC coating with ESD technique.](image-url)
the surface of the coated metal through the partial gaps between the splashes [15].

3.2 Tribological behavior

Figure 4a shows the graph of the wear rate and friction coefficients obtained from the wear test, Figure 4b shows the wear rate of uncoated AISI M2. Figure 4c shows the wear of AISI M2 coated with TiC electrode, and Figure 4d shows the wear of AISI M2 steel coated with WC electrode.

According to the graph given in Figure 4a, the wear rates of uncoated, TiC-coated, and WC-coated samples were calculated as $227 \times 10^{-6}$, $183 \times 10^{-6}$, and $89 \times 10^{-6}$ mm$^3$/Nm, respectively, and the friction coefficients were 0.25, 0.24, and 0.22, respectively. When the wear rates and friction coefficients were examined, the highest values were obtained in the uncoated AISI M2 steel, and the lowest values were obtained in the sample coated with WC.

Figure 4b–d shows the wear areas and scar depths obtained by surface scanning after the dry environment wear test on the SEM images. The wear areas and scar depths of uncoated, TiC-coated, and WC-coated AISI M2 steel obtained by surface scanning were determined as 99.068 mm$^2$ – 20.6 µm, 7.304 mm$^2$ – 18.2 µm, and 3.557 mm$^2$ – 9.82 µm, respectively. Track depths are lower than the coating layer. This shows that the wear is in the coating layer and does not reach the matrix. According to the wear areas and scar depth, the highest values are in uncoated AISI M2 steel, and the lowest are in WC-coated AISI M2 steel.

On the other hand, when the SEM images of the wear marks are examined, abrasive and adhesive wear mechanisms are seen in the dry wear test on the uncoated sample. Moreover, delamination and micro scratches caused by the abrasive ball are clearly identified. In coating with TiC, there are abrasive wear types as well as broken particles, micro-cracks, and deformation areas. In coating with WC, adhesive wear type is mostly seen. In addition, local micro

Figure 4: (a) Wear rate/friction coefficient graph. SEM images of wear marks of (b) uncoated, (c) TiC-coated, and (d) WC-coated AISI M2 steel.
scratches and flaking areas are also clearly observed. Although the TiC electrode-coated sample has higher hardness than the WC electrode-coated sample, the wear values were found to be lower in the WC coating. In TiC coating, the layer exhibits brittle behavior because it is harder. Particles breaking off from the coating layer due to fatigue under repeated loads cause plastic deformation on the surface. However, Hertz forces occurring in the contact areas cause mechanical stresses. Exceeding critical limit values triggers the formation and propagation of cracks on hard surfaces, causing particles to break off more easily from the material [21,22]. This explains why the wear values are weaker in the coating made with TiC electrode, although the layer thickness and microhardness are higher.

### 3.3 Electrochemical corrosion analysis

The data obtained from the electrochemical corrosion test performed at room temperature on uncoated and ESD-coated AISI M2 steel with TiC and WC electrodes are given in Table 3, and the Tafel curves are given in Figure 5.

**Table 3:** Electrochemical corrosion test values of uncoated and coated AISI M2

<table>
<thead>
<tr>
<th>AISI M2</th>
<th>Ecor (mV)</th>
<th>Icor (µA)</th>
<th>Corrosion rate (MPY)</th>
<th>Rp (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>−464</td>
<td>57.60</td>
<td>10.40</td>
<td>0.135</td>
</tr>
<tr>
<td>WC-coated</td>
<td>−516</td>
<td>24.00</td>
<td>6.230</td>
<td>1.12</td>
</tr>
<tr>
<td>TiC-coated</td>
<td>−457</td>
<td>17.00</td>
<td>3.077</td>
<td>7.96</td>
</tr>
</tbody>
</table>

Figure 6 shows the SEM images and EDX results taken from the surface after corrosion tests.

When Table 3 and Figure 5 are examined, it is understood that while the Ecor values of TiC and uncoated samples are close to each other, WC is on the more negative side. Icor values were obtained as 57.60, 24.00, and 17.00 µA in uncoated, WC-coated, and TiC-coated AISI M2 steel, respectively. Icor values decreased with coating. Corrosion resistance improved 2–3 times compared to the uncoated sample. The presence of cracks can be seen in the SEM images taken after the corrosion test (Figure 6) from the TiC-coated and WC-coated sample surfaces. Cl⁻ ions behave very aggressively in the NaCl solution and tries to move towards the matrix through the cracks it finds on the surface, causing the onset of metastable pitting corrosion in these regions. At the same time, these ions cause the cathodic reduction of oxygen (OH⁻ formation) and the initiation of pitting. On the other hand, another reason for the increase in corrosion resistance is due to the cermet coating layers formed on the surface. Because these structures have lower conductivity than steels [23,24].

Thus, although local corrosion started from these regions and progressed into the material, the Icor value being lower than the uncoated sample shows that the cracks did not continue into the matrix. There are cracks on the surface caused by high tensile stresses [25] due to thermal incompatibility between consecutive passes. Another indication that corrosion is limited to the coatings applied in the lower pass and cannot progress to the matrix is the absence of cracks between passes in the microstructure images taken from the cross-section (Figure 2).

The electrochemical reactions occurring for TiC (equations (2)–(4)) and WC (equation (5) and (6)) in 3.5% NaCl solution are as follows:

\[
\text{TiC} + \text{O}_2 \rightarrow \text{Ti} + \text{CO}_2
\]  
(2)

\[
2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- \rightarrow 4\text{OH}^-
\]  
(3)

\[
3\text{Ti} + 2\text{O}_2 + 4\text{OH}^- \rightarrow 3\text{TiO}_2 + 2\text{H}_2\text{O} + 4\text{e}^-
\]  
(4)

\[
\text{WC} + 5\text{H}_2\text{O} \rightarrow \text{WO}_3 + \text{CO}_2 + 10\text{H} + 10\text{e}^-
\]  
(5)

\[
2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- \rightarrow 4\text{OH}^-
\]  
(6)

According to these reactions, TiO₂ and WO₃ compounds emerge as corrosion products. WC reacts with NaCl and is oxidized in solution. TiC, on the other hand, forms a protective stable TiO₂ layer at the interface in its reaction with NaCl [26]. This is another indicator of the high corrosion resistance of the sample coated with TiC electrode.

In corrosion resistance analyses, it is necessary to consider the electrochemical stability of each element contained in the material. Therefore, according to the XRD
graph of the coatings (Figure 3), the effect of the $M_23C_6$ and $M_7C_3$ ($M = \text{Cr, Fe}$) phases determined on the surface as a result of alloying during the coating on the corrosion resistance cannot be ignored. The corrosion resistance of Cr is higher than that of Fe, and in environments where acidic aqueous electrolytics are present, Fe and Cr oxidize and turn into $\text{Fe}_2\text{O}_3$, $\text{Fe}_3\text{O}_4$, $\text{Cr}_2\text{O}_3$, $\text{Cr}_2\text{O}_3$ creating a passive film on the surface, causing corrosion to decrease [27]. On the other hand, corrosion resistance ($R_p$) and corrosion rate: $0.135 \, \text{k}\Omega - 10.40 \, \text{MPY}$, $1.12 \, \text{k}\Omega - 6.230 \, \text{MPY}$, $7.96 \, \text{k}\Omega - 3.077 \, \text{MPY}$ were obtained in uncoated, WC-coated, and TiC-coated AISI M2 steel, respectively.

The fact that corrosion resistance is higher and the corrosion rate is lower in coated samples is a clear indication that corrosion resistance increases with coating. Low corrosion current and high corrosion potential are considered high corrosion resistance in the material [28,29]. It is clearly seen that as the corrosion rate decreases, the corrosion resistance of TiC and WC coatings increases using the ESD technique.

4 Conclusion

The results obtained in coating the HSS surface with TiC electrode and WC electrode using the ESD technique are as follows:

- The surface of AISI M2 steel was successfully coated with TiC and WC electrodes using the ESD technique.

![Figures of AISI M2 after corrosion tests: (a) uncoated, coated with (b) TiC and (c) WC.](image-url)
The coating layer has a homogeneous, flat, and continuous structure and contains small porosities.

The layer thickness hardness is 1,558 HV0.05 for TiC coating and 1,322 HV0.05 for WC coating, and the surface hardness of AISI M2 steel increased by 4–5 times.

According to the XRD pattern, in the coating layer, TiC, Ti$_7$C$_6$, M$_2$C$_6$, and M$_7$C$_3$ phases were detected for TiC coating, and WC, Fe$_3$W$_2$C, M$_2$C$_6$, and M$_7$C$_3$ phases were detected for WC coating.

While the wear rate and friction coefficient values decreased with TiC and WC coating of AISI M2 steel, the lowest wear values were obtained in WC coating.

According to the electrochemical corrosion results, Ecor values are close to each other and the lowest value is in WC-coated AISI M2 steel.

Icor values decrease with coating and the values are uncoated AISI M2 > WC coated > TiC-coated.

In coating with ESD technique, while corrosion rate values are decreasing, corrosion resistance values are increasing, and the lowest corrosion rate and highest corrosion resistance were detected in TiC coating.

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**Data availability statement:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**References**


