Influences of the current density on the performances of the chrome-plated layer in deterministic electroplating repair

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Abstract. Deterministic electroplating repair is a novel method for rapidly repairing the attrited parts. By the qualitative contrast and quantitative comparison, influences of the current density on performances of the chrome-plated layer were concluded in this study. The chrome-plated layers were fabricated under different current densities when the other parameters were kept constant. Hardnesses, thicknesses and components, surface morphologies and roughnesses, and wearability of the chrome-plated layers were detected by the Vickers hardness tester, scanning electron microscope / energy dispersive X-ray detector, digital microscope in the 3D imaging mode, and the ball-milling instrument with profilograph, respectively. In order to scientifically evaluate each factor, the experimental data was normalized. A comprehensive evaluation model was founded to quantitative analyse influence of the current density based on analytic hierarchy process method and the weighted evaluation method. The calculated comprehensive evaluation indexes corresponding to current density of 40 A/dm², 45 A/dm², 50 A/dm², 55 A/dm², 60 A/dm², and 65 A/dm² were 0.2246, 0.4850, 0.4799, 0.4922, 0.8672, and 0.1381, respectively. Experimental results indicate that final optimal option was 60 A/dm², and the priority orders were 60 A/dm², 55 A/dm², 45 A/dm², 50 A/dm², 40 A/dm², and 65 A/dm².

1. Introduction

Deterministic electroplating repair is a new and practical method for rapidly repairing the attrited parts, which is based on the deterministic surfacing theory [1] and electroplating technique [2, 3]. Schematic diagram of the deterministic electroplating repair system is shown in the figure 1. Original profile of the attrited part is obtained by three-coordinate measuring machine. Through subtracting the expected shape from the original profile, theoretical distribution of the optimal deposition layer is calculated. The electroplating solution is sucked from the container to the nozzle head by the peristaltic pump and is absorbed back to the container by the atmospheric pressure generated from the vacuum ejector. Through controlling concentration of the electroplating solution and the current density between the anode and the attrited part, shape of the deposition function and its efficiency can be kept steady. Distribution of the dwelling time can be achieved by the Fourier transform and convolution operation based on the theoretical distribution of the optimal deposition layer and the deposition function [4]. By controlling movement of the nozzle head which is installed on the three-dimension (3D) motion platform according to distribution of dwelling time, the attrited part can be deterministically repaired. Different from electro-brush plating [5] and electro-bath plating [6], parameters in the deterministic electroplating repair should be accurately controlled, because stability and veracity of the deposition
function is the foundation of the deterministic electroplating method. Among these parameters, current density is an important factor, which affects efficiency of the deposition function and performance of the chrome-plated layer. Thus, investigation of the influences of current density was conducted in this study. The chrome-plated layers were fabricated under the different current densities when the other parameters were kept constant. Then, hardnesses, thicknesses and components, surface morphologies and roughnesses, and wearability of the chrome-plated layers were detected respectively.

![Schematic diagram of the deterministic electroplating repair system.](image)

**Figure 1.** Schematic diagram of the deterministic electroplating repair system.

### 2. Experimental parameters

The chrome-plated layer was deposited on the specimen 1045 steel. The pressure, concentration, and time of the wet sand blasting were 0.48 MPa, 10-15%, and 15 min, respectively. The activations before formal plating consisted of the dipping and rinse for 5 min, warm-up for 60 s, countercurrent at 26 A/dm² for 80 s, and primary plating at 6 A/dm². The current gradually raised 70 A/dm² in 10 min, which started the concussive plating. The concussive plating stood for 4 min. Afterwards, the formal plating was conducted for 116 min, which meant that the total effective plating time was 120 min, and the investigated current densities were 40 A/dm², 45 A/dm², 50 A/dm², 55 A/dm², 60 A/dm², and 65 A/dm², respectively. When preparations of the chrome-plated layers were finished, performances of the layers were studied, including the hardness detection, thickness measurement, component analysis, surface morphology investigation, roughness examination, and wearability testing.

### 3. Results and discussions

#### 3.1. Hardness detection

Hardnesses of the chrome-plated layers were detected by the Vickers hardness tester. The values of hardnesses of the chrome-plated layers corresponding to the current densities 40 A/dm², 45 A/dm², 50 A/dm², 55 A/dm², 60 A/dm², and 65 A/dm² were 884 HV0.1, 845 HV0.1, 855 HV0.1, 855 HV0.1, 905 HV0.1, and 874 HV0.1, respectively, which were obviously larger than hardness of the substrate (specimen 1045 steel) 192 HV0.1. Hardness of the chrome-plated layer did not increase or decrease by degrees along with increase of the current density. The best option was 60 A/dm² and the worst option was 45 A/dm². Target of deterministic electroplating repair was the attrited part, and its usability can be improved by fabricating the high-hardness chrome-plated layer at the worn region.
3.2. Thickness measurement and component analysis

Thicknesses and components of the chrome-plated layers were measured by the scanning electron microscope and energy dispersive X-ray detector [7, 8], respectively, as shown in the figure 2, and the results were summarized in table 1. It could be found that concentrations of the Cr element ranged from 97.8% to 98.36% and the average was 98.09%, which indicated that component consistencies of the chrome-plated layers in the six experiments were excellent. Influence of the current density to the plating efficiency was fluctuant. The best option was 60 A/dm² and the worst option was 65 A/dm². The major reason was that the increase of current density would raise the over-potential for the Hydrogen (H) evolution and that for the Cr evolution [9]. The average thickness of the chrome-plated layer was 157 µm when the current density was 60 A/dm².

Table 1. The summarized results of thickness measurement and component analysis.

| Current density | Thickness measurement | Components analysis |
|-----------------|-----------------------|---------------------|
|                 | Position 1            | Position 2          | Average     | Cr (wt %)  | C (wt %) |
| 40 A/dm²       | 78.4 µm               | 70.8 µm             | 74.6 µm     | 98.08%     | 1.92%    |
| 45 A/dm²       | 120 µm                | 119 µm              | 119.5 µm    | 98.36%     | 1.64%    |
| 50 A/dm²       | 141 µm                | 131 µm              | 136 µm      | 98.15%     | 1.85%    |
| 55 A/dm²       | 82.5 µm               | 90.3 µm             | 86.4 µm     | 97.97%     | 2.03%    |
| 60 A/dm²       | 160 µm                | 154 µm              | 157 µm      | 97.8%      | 2.2%     |
| 65 A/dm²       | 61.4 µm               | 65 µm               | 63.2 µm     | 98.15%     | 1.85%    |

3.3. Surface morphology investigation and roughness examination

Surface morphologies and roughnesses of the chrome-plated layers were investigated by the digital microscope in the 3D imaging mode [10], as shown in the figure 3. The calculated roughness average (Ra) and the selection of ten-point height of irregularities (Rz) was summarized in table 2.

Table 2. Summary of the calculated Ra and Rz of the chrome-plated layers.

| Current density | Surface roughness of the cross-sectional line |
|-----------------|-----------------------------------------------|
|                 | Ra (µm)    | Rz (µm) |
| 40 A/dm²        | 8.572      | 31.88   |
| 45 A/dm²        | 6.315      | 27.68   |
| 50 A/dm²        | 6.182      | 25.58   |
| 55 A/dm²        | 5.659      | 20.23   |
| 60 A/dm²        | 7.114      | 29.89   |
| 65 A/dm²        | 7.375      | 31.83   |
Figure 2. Thickness and component analysis of chrome-plated layer. (a) current density was 40 A/dm². (b) current density was 45 A/dm². (c) current density was 50 A/dm². (d) current density was 55 A/dm². (e) current density was 60 A/dm². (f) current density was 65 A/dm².
Figure 3. Surface morphologies and roughnesses of the chrome-plated layers. (a) current density was 40 A/dm$^2$. (b) current density was 45 A/dm$^2$. (c) current density was 50 A/dm$^2$. (d) current density was 55 A/dm$^2$. (e) current density was 60 A/dm$^2$. (f) current density was 65 A/dm$^2$. 
3.4. Wearability testing

The chrome-plated layers were polished for 60 min by the ball-milling instrument, and results of the wearability testing were achieved by the profilograph. It could be calculated that the wearing rates were 1.10 \( \mu m/\text{min} \), 0.95 \( \mu m/\text{min} \), 1.18 \( \mu m/\text{min} \), 0.90 \( \mu m/\text{min} \), 0.83 \( \mu m/\text{min} \), and 1.18 \( \mu m/\text{min} \) corresponding to the current density of 40 A/dm\(^2\), 45 A/dm\(^2\), 50 A/dm\(^2\), 55 A/dm\(^2\), 60 A/dm\(^2\), and 65 A/dm\(^2\). Especially when the current density was 65 A/dm\(^2\), depth of the polished spot was larger than thickness of the chrome-plated layer, which indicated that the polishing process penetrated through the chrome-plated layer and into the substrate. Wearability of the chrome-plated layer affected the useful life of the repaired part. The smaller the wearing rate is, the larger the useful life is.

4. Summaries

Influence of the current density to performance of the chrome-plated layer was evaluated based on the obtained experimental data, including hardness, thickness (plating efficiency), surface roughness (Ra and Rz), and wearability (wearing rate). In order to scientifically evaluate each factor, the data was normalized, as shown in the Table 3. For the positive factors, such as the hardness and the plating efficiency, normalization was achieved by the Eq. 1. Meanwhile, for the negative factors, such as the surface roughness and wearing rate, normalization was obtained by the Eq. 2. Here \( a_i \) and \( b_i \) both represented the experimental data, and \( \alpha_i \) and \( \beta_i \) were the corresponding normalized results.

\[
\alpha_i = \frac{a_i - \min(\{a_i|i=1,2,3,4,5,6\})}{\max(\{a_i|i=1,2,3,4,5,6\}) - \min(\{a_i|i=1,2,3,4,5,6\})}
\]

\[
\beta_i = \frac{\max(\{b_i|i=1,2,3,4,5,6\}) - b_i}{\max(\{b_i|i=1,2,3,4,5,6\}) - \min(\{b_i|i=1,2,3,4,5,6\})}
\]

Table 3 Summary of the normalized data of the evaluation factors.

| Current density (A/dm\(^2\)) | Hardness | Plating efficiency | Surface roughness (\( R_a \)) | \( R_z \) | Wearing rate |
|-------------------------------|----------|-------------------|---------------------------------|------------|--------------|
| 40                            | 0.650    | 0.122             | 0.000                           | 0.000      | 0.229        |
| 45                            | 0.000    | 0.600             | 0.775                           | 0.361      | 0.657        |
| 50                            | 0.167    | 0.776             | 0.820                           | 0.541      | 0.000        |
| 55                            | 0.167    | 0.247             | 1.000                           | 1.000      | 0.800        |
| 60                            | 1.000    | 1.000             | 0.501                           | 0.171      | 1.000        |
| 65                            | 0.483    | 0.000             | 0.411                           | 0.004      | 0.000        |

A comprehensive evaluation model was founded to quantitative analyze influence of the current density based on the analytic hierarchy process (AHP) method and weighted evaluation method [11]. Therefore, it would be found that relationship between Ra and Rz was highly linear correlation, which indicated that the five evaluation factors could be divided into four groups. Fine surface roughness of the repaired part would avoid the secondary machining of ultra-hard chrome-plated layer, which was the remarkable advantage of deterministic electroplating repair process. However, surface roughness Ra and Rz of the chrome-plated layers were mainly decided by pretreatment of the attrited part before repair, and the electroplating process had few influences. Thus, weight of evaluation factors for Ra and Rz were both 0.1. Meanwhile, the plating efficiency was the most important factors, which decided the final repairing efficiency. Therefore, weight for the plating efficiency was 0.4. Furthermore, the hardness determined the usability of the repaired part and the wearing rate decided its useful life, so they shared the rest of weight 0.4. According to the above analysis, the final comprehensive evaluation
model was obtained, as shown in Eq. 3. Here \( E \) was the comprehensive evaluation index. \( n_{\text{hardness}} \), \( n_{\text{plating\_efficiency}}, n_{R_a}, n_{R_c}, \) and \( n_{\text{wearing\_rate}} \) were the normalized data in Table 3, respectively.

\[
E = 0.2 \cdot n_{\text{hardness}} + 0.4 \cdot n_{\text{plating\_efficiency}} + 0.1 \cdot n_{R_a} + 0.1 \cdot n_{R_c} + 0.2 \cdot n_{\text{wearing\_rate}}
\] (3)

The calculated comprehensive evaluation indexes corresponding to current density of 40 A/dm\(^2\), 45 A/dm\(^2\), 50 A/dm\(^2\), 55 A/dm\(^2\), 60 A/dm\(^2\), and 65 A/dm\(^2\) were 0.2246, 0.4850, 0.4799, 0.4922, 0.8672, and 0.1381, respectively. It could be observed that the final optimal option was 60 A/dm\(^2\), and the priority orders were 55 A/dm\(^2\), 45 A/dm\(^2\), 50 A/dm\(^2\), 40 A/dm\(^2\), and 65 A/dm\(^2\).

5. Conclusions
Investigation of the influences of current density was conducted in this study. Hardnesses, thicknesses and components, surface morphologies and roughnesses, and wearability of chrome-plated layers were detected respectively. Based on the analytic hierarchy process (AHP) method and the weighted evaluation method, a comprehensive evaluation model was founded to quantitatively analyze influence of the current density. Experimental results indicate that the final optimal option was 60 A/dm\(^2\).

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