

General paper

Mechanism of Corrosion Resistance Degradation of Cr-Plated Parts Due to Heat Treatment and Its Prevention

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Abstract: The mechanism of decrease in the corrosion resistance of Cr-plated parts when they are subjected to a heating process and measures for preventing the degradation are studied. When postfinishing is performed after the Cr-plating process, cracks in the Cr layer are closed as a result of plastic flow on the topmost surface layer. When the residual stress in the Cr layer becomes compressive due to the postfinishing, the cracks are completely closed, resulting in a high corrosion resistance. The residual stress in the Cr layer changes from compressive to tensile following heat treatment. When the residual stress becomes tensile, the cracks in the Cr layer which were closed during postfinishing open once again, resulting in a decrease in the corrosion resistance. We speculated that the change of residual stress from compressive to tensile is caused by the shrinkage of the Cr layer due to heat treatment and the difference in the coefficients of thermal expansion between the substrate (steel) and Cr layer, as well as the release of residual stress generated during processing. In order to prevent the decrease of corrosion resistance under heat treatment, it is effective to apply compressive stress which exceeds the level of change in residual stress due to heat treatment to the Cr layer during postfinishing, after the Cr plating process.

Key words: Cr-Plating layer, Postfinishing, Corrosion resistance, Residual stress, X-ray stress measurement, Heat treatment

1. INTRODUCTION

Since hard Cr-plating offers high corrosion and wear resistance and a low coefficient of friction, it has been used in various industries, including the automobile industry, in such components as piston rods used for shock absorbers, piston rings and cylinder liners, as well as for shafts of hydraulic equipment, rolls for printing and rolling, and metal molds [1,2]. Cr-plating layers usually have fine cracks (channel cracks, hereafter), and the steel substrates rust due to infiltration of corrosive liquids through the channel cracks. Therefore, corrosion resistance is influenced by not only the thickness of the Cr-plating layers but also the crack width, the crack depth and the number of cracks [3]. In addition, it is widely recognized that by performing such a postfinishing process as buffing and superfinishing after the plating process, channel cracks can be filled, resulting in the improvement of corrosion resistance [2]. However, the corrosion resistance of Cr-plated parts improved by means of a postfinishing process may decrease upon heat treatment performed after the postfinishing.

In the present study, the mechanism of corrosion resistance degradation during heat treatment is clarified and preventive measures are discussed, focusing on the residual stress of the Cr-plating layer as determined by the X-ray diffraction method.

2. CORROSION RESISTANCE OF Cr-PLATED STEEL RODS

A steel rod with an outer diameter of 20mm and length of 350mm (JIS S45C) was used. A 20 μ m-thick Cr layer was electroplated on the outer surface of the rod under the conditions summarized in Table 1. Then,

a postfinishing process was carried out under the conditions summarized in Table 2 using a through-feed centerless polishing machine (OD-2, Nisshinbo Industries, Inc.) to which a buffing wheel (Bear-tex GD-VF, Kure-Norton, Co. Ltd.) with an outer diameter of 305mm and width of 100mm was attached. The surfaces of the Cr-plating layer before and after postfinishing were observed by scanning electron microscopy (SEM). Furthermore, the neutral salt spray test (NSST, JIS Z2371) was carried out to evaluate the corrosion resistance of the Cr-plating layer before and after postfinishing.

Figure 1 shows SEM micrographs of the surfaces of the Cr-plating layer as deposited and after postfinishing, and the external appearance of the samples after the NSST for 24h and 168h. It is confirmed that postfinishing induces plastic flow on the topmost surface of the Cr-plating layer, resulting in the closure of the channel cracks. Furthermore, corrosion resistance of the Cr-plated layer was increased by postfinishing.

Table 1. Plating conditions of steel rods.

CrO ₃ /SO ₄ , $\times 10^{-3}$ kg/L	250/ 3.5
Catalyst (organo sulfonic acid), %	100
Bath temperature, K	333
Current density, A/dm ²	60

Table 2. Conditions of postfinishing.

Outer diameter of samples, mm	ϕ 20	ϕ 12.5
Feed speed, mm/s	50	
Load voltage, V	200	
Load current, A	5	3
Wheel peripheral speed, m/s	33	
Buffing wheel	Bear-tex GD-VF	

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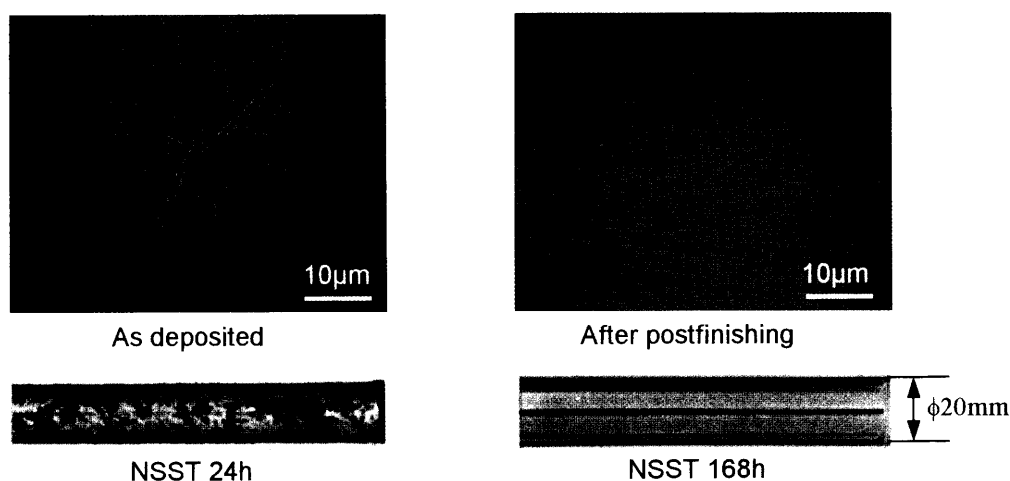


Fig.1. SEM micrographs of Cr plated surface as deposited and after postfinishing, and external appearance of samples after NSSTs for 24h and 168h.

3. CORROSION RESISTANCE DEGRADATION OF Cr-PLATED PARTS

According to the US standard, QQ-C-320B, when parts with surface hardness of 36HRC or higher are plated with Cr, heat treatment at $464 \pm 14\text{K}$ should be carried out within 4h of the deposition of Cr to eliminate hydrogen brittleness. In the case of sliding parts such as piston rods, the temperature of these parts may increase to approximately 423K during the operation. The corrosion resistance of such Cr-plated parts may decrease due to this heat treatment. Therefore, comparisons of the corrosion resistance and the surface conditions of the plating layer before and after heat treatment were carried out.

A steel rod with an outer diameter of 12.5mm and length of 60mm (JIS S25C) was used. A $20\mu\text{m}$ -thick Cr layer was electroplated onto the outer surface of the rod sample under the conditions summarized in Table 1, the postfinishing process was carried out under the conditions in Table 2, using a through-feed centerless polishing machine described in chapter 2. The samples were

Table 3. Results of NSST (JIS Z2371).

Heat treatment	Corrosion resistance NSST 345.6ks (96h)
As postfinished (before heat treatment)	RN 10
423K for 7.2ks (2h)	RN 7~9
523K for 7.2ks (2h)	RN 6~8

held at a constant temperature of 423K or 523K for 2h, and then cooled to room temperature; the NSST (JIS Z2371) was then performed to evaluate the corrosion resistance of the samples. The surfaces of the Cr-plating layer before and after heat treatment were observed by SEM.

Table 3 summarizes the results of the NSST. The rating number (RN) in Table 3 represents the percentage of the corroded area to the total area determined according to the method of the corrosion resistance test for metallic coatings (JIS H8502), RN10 indicates that the sample was not corroded; as the RN number decreases, corrosion resistance becomes inferior. Figure 2 shows

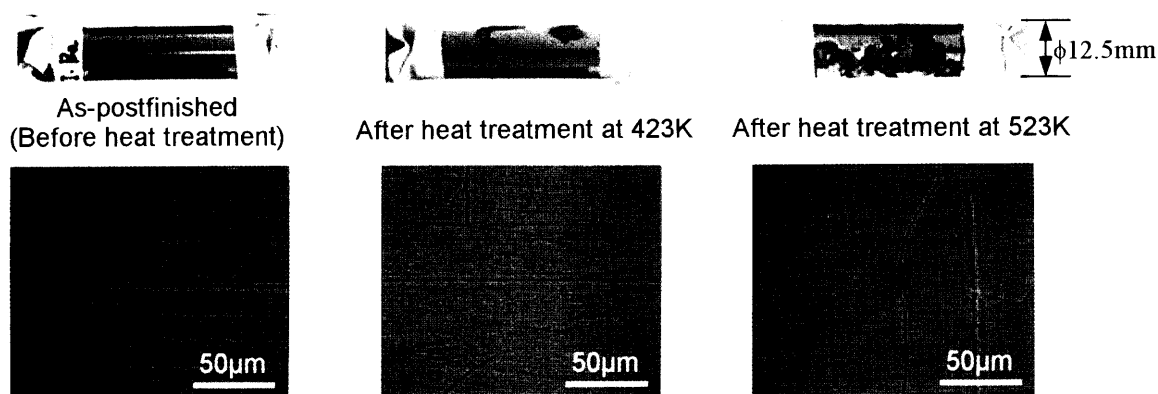


Fig.2. External appearance of samples after NSST for 96h and SEM micrographs of surface of Cr-plating layer before and after heat treatment at 423K and 523K.

the external appearance of the samples after the NSST for 96h and SEM micrographs of the surface of the Cr-plating layer before and after heat treatment at 423K and 523K. As shown in the SEM micrographs, the cracks, which were closed during the postfinishing performed after the plating process, opened again during heat treatment. It was found that corrosion initiates from the reopened cracks.

According to Knödler [4], the density of the Cr-plating layer at room temperature (Table 4) is lower than that of conventional Cr, which indicates the presence of many lattice defects (vacancies) in the Cr-plating layer. Knödler reported that the density of the Cr-plating layer increases upon heat treatment at 1223K; in other words, the Cr-plating layer shrinks upon heat treatment at this temperature. It can be supposed that heat treatment facilitate the diffusion and disappearance of vacancies in the Cr-plating layer. Although no reports have been made regarding the samples heat-treated at 423K, we believe that there is a possibility that vacancies diffuse in the samples heat-treated at relatively low temperatures, similar to the samples heat-treated at 1223 K, and that the Cr-plating layer shrinks with the diffusion of vacancies.

4. X-RAY STRESS MEASUREMENT

In X-ray stress measurement, the $\sin^2\psi$ method [5] is generally used. In the standard method for X-ray stress measurement [5], five or more ψ angles are generally selected from a wide range. Here, the ψ -angle is the angle between the normal to the sample surface and the normal to the crystal plane. Cr-plating layers appear {111} oriented. When the {111} plane of the cubic lattice is parallel to the plating surface, the 211 diffraction appears

Table 4. Density of Cr-plating layer.

	Density, $\times 10^3$ kg/m ³
As deposited	6.971~6.995
After heat treatment, 1223K	7.148
Chromium	7.19

Table 5. Conditions of X-ray stress measurement.

X-ray optics	Parallel beam ψ -constant
Characteristic X-rays	Cr-K α
Wavelength, nm	0.229100
Filter	V
Tube voltage, kV	30
Tube current, mA	8
Irradiated area, mm ²	28.3
Fixed time, s	2
Slit divergence angle, deg	Incident: 1, Receiving: 1
Diffraction plane	Cr {211}
Scan angle, deg	143<2 θ <165
Step width, deg	0.25
ψ angle, deg	Approximately 19.5, 61.9

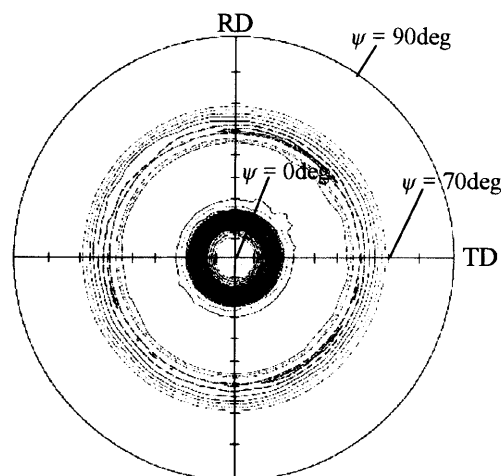


Fig.3. Typical 211 pole figure of Cr-plating layer.

at approximately $\psi_1=19.5\text{deg}$ and $\psi_2=61.9\text{deg}$, as shown in the {211} pole figure typical of the Cr-plating layer (ψ measurement range of 0 to 70deg) shown in Fig.3. For the stress measurement of materials having such a texture, a method in which the crystallographic azimuthal relationship is utilized is under consideration [6-8]. In this study, such a relationship [9] is considered and ψ angles corresponding to the high intensity peaks were selected at around $\psi_1=19.5\text{deg}$ and $\psi_2=61.9\text{deg}$. Then, diffraction angles, $2\theta(\psi_1)$ and $2\theta(\psi_2)$, at those ψ angles were measured, and residual stress was calculated using Eq. (1),

$$\sigma = K \cdot \frac{2\theta(\psi_1) - 2\theta(\psi_2)}{\sin^2 \psi_1 - \sin^2 \psi_2}, \quad (1)$$

where, 2θ is the diffraction angle determined by Bragg's law and K is the X-ray stress constant of the Cr-plating layer.

In this study, the stress constant $K=-247\text{MPa/deg}$ [10] was used. Table 5 summarizes the conditions of X-ray stress measurement. The X-ray stress measurement apparatus PSF-2M (Rigaku Co.) was used.

5. CHANGES IN Cr-PLATING LAYER DUE TO HEAT TREATMENT

5.1. Shrinkage of Cr-Plating Layer

In order to clarify the behavior of the Cr-plating layer during heat treatment, specimens of only the Cr-plating layer were produced, and the change of the dimensions and the diffraction X-ray width (half-width) were measured.

5.1.1. Experimental

An approximately 3mm-thick Cr layer was electroplated onto a steel plate (JIS S45C, thickness 5mm) under the conditions summarized in Table 6. Then the steel plate was removed completely to obtain a specimen composed of the Cr-plating layer alone, with the dimensions of $73 \times 15 \times 2\text{mm}^3$. The samples were held at 373K, 423K, 473K or 523K for 2h, before cooling to room temperature. The length of the specimens in the

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Table 6. Plating conditions of steel plate.

CrO ₃ /SO ₄ , ×10 ⁻³ kg/L	250/ 2.5
Bath temperature, K	318
Current density, A/dm ²	30

longitudinal direction was measured five times using a micrometer. Based on the change in the length before and after heat treatment, the dimensional change ratio was calculated. In addition, the half-width of the X-ray profile in the Cr-plating layer was measured at $\psi=19.5\text{deg}$ under the conditions given in Table 5.

5.1.2. Results

Figure 4 (a) shows the relationship between holding temperature and dimensional change ratio. At the holding temperature of 423K or higher, a remarkable shrinkage of the Cr-plating layer was observed; the amount of shrinkage increases with increasing holding temperature. It can be supposed that this shrinkage is caused by the diffusion and disappearance of vacancies in the plating layer upon heat treatment.

Figure 4 (b) shows the relationship between the holding temperature and the half-width of the X-ray line. At holding temperatures of 423K and higher, the half-width decreases. The half-width of the X-ray line is defined by the microscopic lattice strain (microstrain, hereafter) and the size of the crystallite [9]. Decreasing X-ray line half width indicates that at holding temperatures of 423K and higher, relaxation of microstrain or growth of the crystallite occurs.

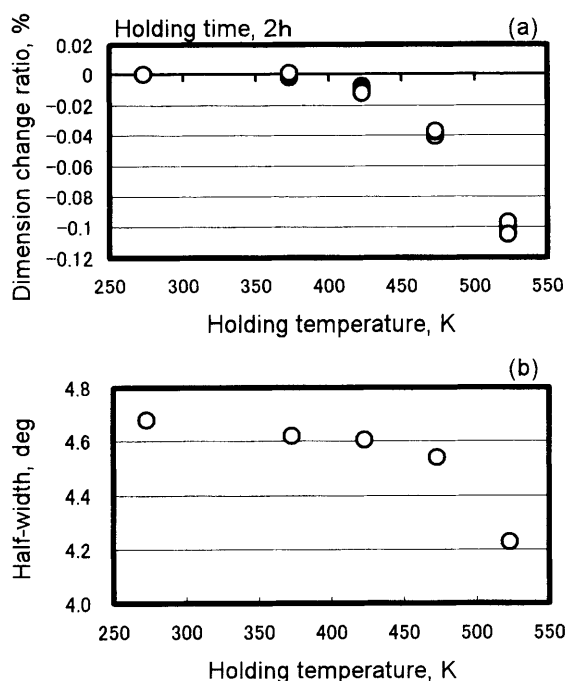


Fig. 4. Relationships between the dimension change ratio (a), half-width of X-ray profile (b) (211 diffraction, Cr-K α radiation) and holding temperatures.

5.2. Change in Residual Stress in Cr-Plating Layer on Steel Substrate Upon Heat Treatment

Since the Cr-plating layer is restricted by the substrate, it is considered that the crack width, crack density and residual stress may change due to shrinkage of the Cr-plating layer resulting from heat treatment. The changes in these values were experimentally measured. Experiments were carried out immediately after plating, i.e., without the postfinishing process.

5.2.1. Experimental

A steel rod with an outer diameter of 12.5mm and length of 300mm (JIS S25C) was used. A 20 μm -thick layer of Cr was plated on the outer surface of the rod sample under the conditions summarized in Table 1. The samples were annealed at 373K, 423K, 473K or 523K for 2h and then cooled to room temperature. The width of the cracks and the crack density per unit length were measured by SEM and using a microscope, respectively. The average width of five selected cracks was calculated. To determine the crack density per unit length, five 1mm-long straight lines (corresponding to 100mm in a $\times 100$ magnified micrograph) were drawn on the micrographs, and the number of cracks intersecting these lines was counted. The residual stress in Cr-plating layers was measured by the X-ray technique under conditions summarized in Table 5. Furthermore, the half-width of X-ray profiles of Cr-plating layers held at each holding temperature and then cooled was measured at $\psi=19.5\text{deg}$ under the conditions of X-ray diffraction shown in Table 5.

5.2.2. Results and discussion

Figure 5 shows the relationships between holding temperature, crack width (a), crack density (b), residual stress (c) and half-width of X-ray profile (d) for the samples which were plated but not subjected to postfinishing. Figure 6 shows SEM micrographs of the surface of the Cr-plating layer before (as-deposited) and after heat treatment at 523K for 2h.

As shown in Figs.5 and 6, with increasing holding temperature, both crack width and crack density increase, while residual stress decreases. As discussed in the previous section, the Cr-plating layer shrinks upon heat treatment. When the Cr-plating layer is restricted by the substrate, it is believed that not only the crack width increases, but the residual stress in the plating layer also becomes more tensile. However, in practice, although the crack width increases, the residual stress tends to decrease, leading to generation of new cracks. The following reason can be proposed. When a Cr layer on a substrate is heat-treated, the crack width increases due to the shrinkage of the plating layer, and the residual stress in the plating layer becomes more tensile. However, since the tensile strength of the plating layer is approximately 200MPa, when residual stress in the plating layer exceeds 200MPa, new cracks are generated and the residual stress is relaxed.

Due to the difference in the average coefficient of linear expansion between the Cr-plating layer and the substrate (Cr- $6.5 \times 10^{-6}/\text{K}$, S25C- $12.2 \times 10^{-6}/\text{K}$, at 273 to 373K) [11], new cracks may be generated. If new cracks are gen-

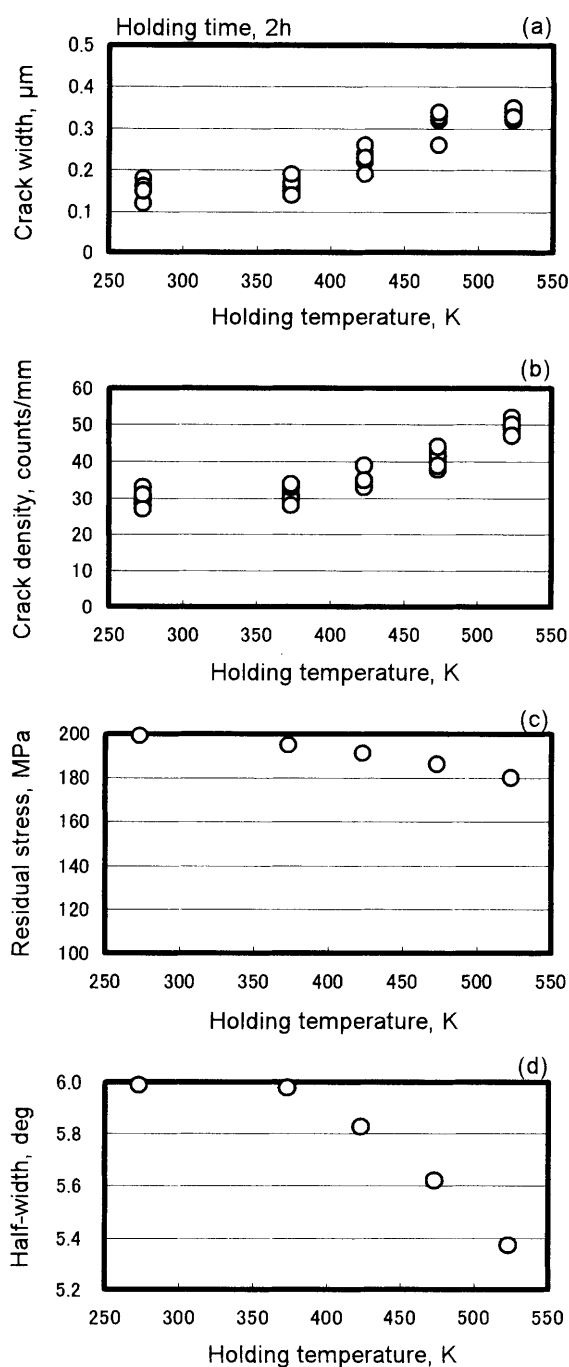


Fig. 5. Relationships between crack width (a), crack density (b), residual stress (c), half-width of X-ray profile (d) (211 diffraction, Cr-K α radiation) and holding temperatures.

erated due to this difference, it is possible that the width of the newly generated cracks will decrease after heat treatment; however, the crack width increases as the whole. Based on this discussion, the influence of shrinkage of the plating layer, rather than the difference in the average coefficient of linear expansion, is thought to play the more important role in the increase of the crack density.

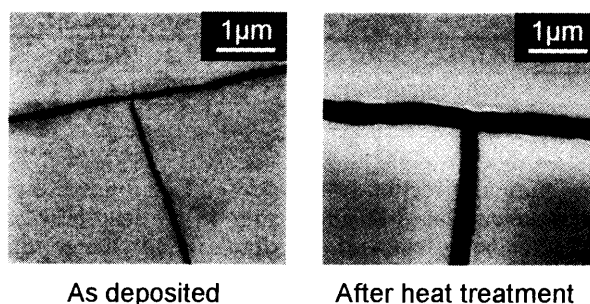


Fig. 6. SEM micrographs of surface of Cr-plating layer as deposited and after heat treatment at 523K for 2h (without post-finishing).

At the holding temperature of 423K, the X-ray line half-width starts to decrease, and crack width and crack density start to increase. Since many vacancies are present in grain boundaries, the size of crystallites increases along with the disappearance of vacancies. In addition, with increasing holding temperature, microstrain is relaxed. The reason for the rapid decrease of the X-ray line half-width at holding temperatures of 423K or higher is that the disappearance of vacancies and relaxation of microstrain are significantly promoted at these temperatures. The X-ray line half-width in this experiment is higher than that obtained in the experiment discussed in section 5.1, which is explained in terms of the difference in plating conditions (plating bath solutions, current density and bath temperature).

When postfinishing is carried out, the residual stress in the Cr-plating layer becomes more compressive due to plastic flow on the top surface of the layer. Furthermore, the behavior of the residual stress in the Cr layer subjected to postfinishing may be different from that having no postfinishing. Then, the residual stress in the Cr-plating layer is next evaluated by changing the postfinishing conditions.

6. RESIDUAL STRESS OF Cr-PLATING LAYER AND CORROSION RESISTANCE

6.1. Experimental

A steel rod with an outer diameter of 20mm and length of 406.5mm (JIS S45C) was used. After 20μm of Cr was plated onto the surface of the rod under the conditions summarized in Table 1, the postfinishing process was carried out by changing the feed speed and load current as summarized in Table 7, using a through-feed center-less polishing machine described in chapter 2.

The residual stress applied to the Cr-plating layer by buffing depends on the processing conditions, such as outer diameter of the sample, feed speed, load voltage and load current of the polishing machine. Therefore, the energy consumed to process a unit area of the outer surface of the sample (energy consumption (W), hereafter) was used as an index of the processing condition. The energy consumption (W) is expressed by Eq. (2),

$$W = \frac{E \cdot I}{v \cdot \pi \cdot d} \quad (2)$$

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where, E and I are the load voltage (V) and load current (current during postfinishing minus current without load, (A)) applied to the motor of the center-less polishing machine, respectively, v is the feed speed (mm/s), π is the ratio of the circumference of the circle to its diameter, and d is the outer diameter of the sample (mm). The unit of W is J/mm^2 .

The residual stress in the Cr-plating layer before and after postfinishing was measured by the X-ray technique. The measurement conditions are listed in Table 5. The residual stresses in two directions, i.e., axial and circumferential, were measured. The samples were annealed at 523K for 2h and cooled to room temperature, before the residual stress was measured. The corrosion resistance of the Cr-plating layer was evaluated based on the RN obtained after the NSST for 96h.

In addition, to clarify the closure condition of the cracks, the cross-sectional morphology of a typical Cr-plating layer after the postfinishing process (prior to heat treatment) was observed by SEM.

6.2. Results and Discussion

Figure 7 shows the relationship between the energy consumption (W) and residual stress in the Cr-plating layer. Solid circles and open circles in Fig.7 represent the residual stress in the axial and circumferential directions of the sample before heat treatment, respectively. Solid squares and open squares represent the residual stress in the axial and circumferential directions of the sample after heat treatment at 523K, respectively. Figure 8 shows the relationship between energy consumption (W) and corrosion resistance of the samples. Open triangles and solid triangles correspond to before and after heat treatment, respectively.

(1) Residual stress and corrosion resistance of samples after postfinishing (before heat treatment)

As shown in Fig.7, compared to the sample A before postfinishing ($W=0J/mm^2$; residual stress in Cr-plating layer, approximately 200MPa), the residual stresses of the Cr-plating layer after postfinishing (before heat treatment) are -259 to 35MPa (axial direction) and -222 to 74MPa (circumferential direction). The residual stresses in the axial and circumferential directions of the sample became more compressive with increasing energy consumption. It is considered that the

cracks close during postfinishing, since postfinishing induces plastic flow on the top surface of the Cr-plating layer, generating compressive residual stress within the layer. With increasing energy consumption (W), the residual stress in the Cr-plating becomes more compressive; however in samples G, H and K, with $W=0.4J/mm^2$ or higher, the rate of increase of the residual stress toward compressive stress decreases. The possible reason is as follows: when postfinishing which induces $W=0.4J/mm^2$ or higher is carried out, friction heat is generated between the sample and the buffing wheel (for example, the surface temperature of sample K is 370K at $W=0.764J/mm^2$), resulting in heating of the samples.

Open triangles in Fig.8 show the relationship between energy consumption (W) and corrosion resistance of the sample after postfinishing (before heat treatment). The residual stress of sample B, which was subjected to postfinishing with $W=0.15J/mm^2$ or lower but not subjected to heat treatment, was tensile; sample B rusted during the NSST for 96h (RN 8). The residual stress of the Cr-plating layer was tensile, it is considered that the cracks in sample B were not completely closed during postfinishing.

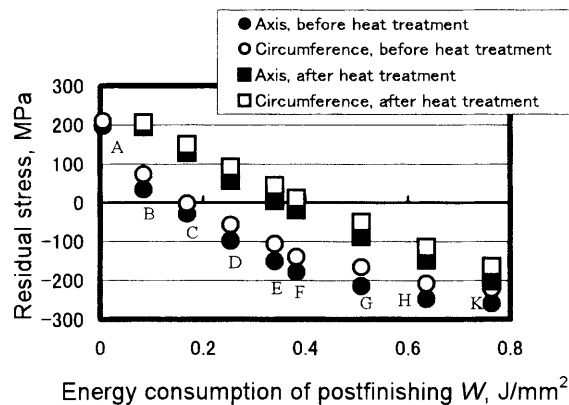


Fig.7. Relationship between the residual stress before and after heat treatment at 523K for 2h and energy consumption (W).

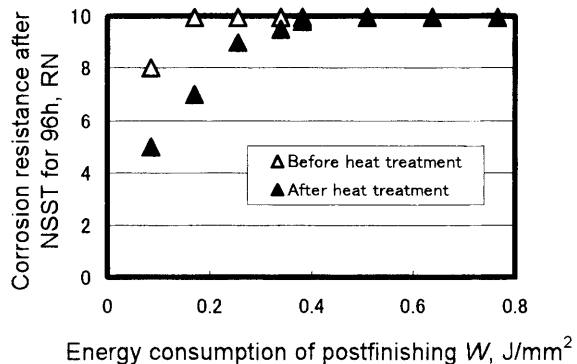


Fig.8. Relationship between corrosion resistance before and after heat treatment at 523K for 2h and energy consumption (W).

Table 7. Conditions of postfinishing.

Sample	Load voltage and current		Feed speed mm/s	Wheel peripheral speed m/s	Energy consumption (W) J/mm ²
	V	A			
A	---	---	---	---	0
B	200	1.0	60	33	0.085
C	200	2.0	60	33	0.170
D	200	2.0	40	33	0.255
E	200	4.0	60	33	0.340
F	200	3.0	40	33	0.382
G	200	2.0	20	33	0.510
H	200	2.5	20	33	0.637
K	200	3.0	20	33	0.764

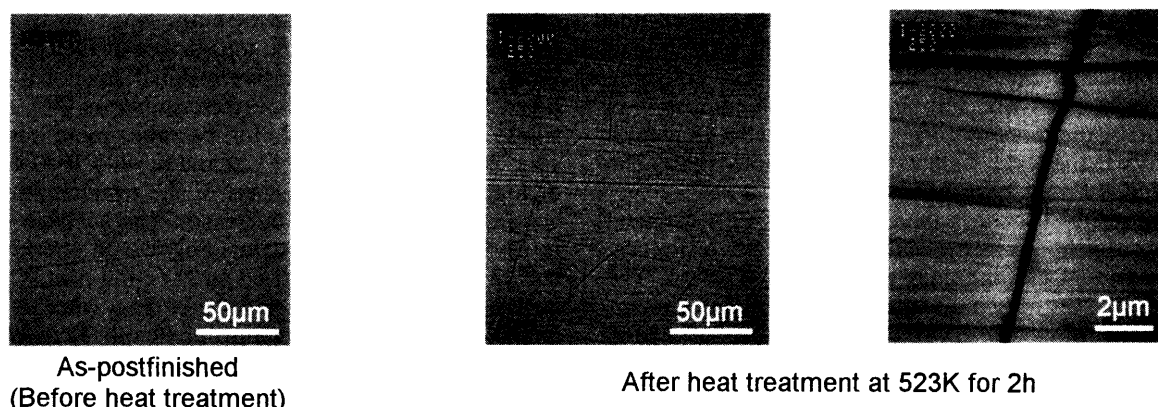


Fig.9. SEM micrographs of surface of Cr-plating layer before and after heat treatment at 523K for 2h (sample C).

(2) Residual stress and corrosion resistance of samples after heat treatment

Solid squares and open squares in Fig.7 represent the residual stress of the Cr-plating layer in the axial and circumferential directions, respectively, of the sample after heat treatment at 523K. The residual stress of the Cr-plating layer after heat treatment at 523K becomes more tensile for all samples. The following three reasons may explain this phenomenon: (1) shrinkage of the Cr-plating layer upon heat treatment, (2) difference in the average coefficients of linear expansion between the Cr-plating layer and the substrate (Cr, $6.5 \times 10^{-6}/K$; steel (S45C), $12.2 \times 10^{-6}/K$; at 273 to 373K) and (3) relaxation of residual stress upon heat treatment.

A correlation was observed between the energy consumption (W) and the residual stress of the Cr-plating layer heat-treated at 523K. The changes in the residual stress upon heat treatment (difference in residual stress before and after heat treatment) in the samples G, H and K ($W=0.4J/mm^2$ or higher) are small compared to those of other samples. As discussed in the previous section, samples subjected to postfinishing with $W=0.4J/mm^2$ or higher may be heated due to the friction heat generated during postfinishing prior to heat treatment.

Solid triangles in Fig.8 show the relationship between energy consumption (W) and corrosion resistance of the sample after heat treatment. The value of energy consumption at which the corrosion resistance of a sample markedly changes after heat treatment corresponds to that at which residual stress of the Cr-plating layer equals approximately 0MPa. If the residual stresses in both the axial and circumferential directions of the sample are compressive even after heat treatment, the corrosion resistance of the sample observed before heat treatment is maintained. However, when the residual stress in either the axial or circumferential direction becomes tensile after heat treatment, the corrosion resistance decreases. It is considered that the cracks which have been closed during postfinishing open again when the residual stress in the sample exceeds 0MPa.

By selecting processing conditions such that the residual stress in the Cr-plating layer is compressive even after heat treatment, the decrease of corrosion resistance upon heat treatment can be prevented.

Figure 9 shows SEM micrographs of the surface of the Cr-plating layer (sample C, $W=0.170J/mm^2$) before and after heat treatment. Immediately after post finishing (before heat treatment), the cracks are closed; however, after heat treatment at 523K, the residual stress of the Cr-plating layer becomes tensile in both the axial and circumferential directions, and cracks are clearly observed.

(3) SEM observation of cross section of Cr-plating layer after postfinishing

Figure 10 shows SEM micrographs of the cross section of the Cr-plating layer (sample D) after postfinishing (before heat treatment). The cracks in the Cr-plating layer at depths of 1 to $2\mu m$ from the topmost surface of the layer are closed by postfinishing. The cracks existing at depths other than the above range remain open after postfinishing. The residual stress of the Cr-plating layer is calculated as the average of the residual stresses at the depths to which characteristic Cr-K α X-rays can penetrate (approximately $14\mu m$ at $\psi_1=19.5deg$, approximately $6\mu m$ at $\psi_2=61.9deg$). Since the cracks existing at depths of 1 to $2\mu m$ from the topmost surface are closed by postfinishing, the residual stress at the topmost surface of the Cr-plating layer is more compressive than the measured value. It is considered that there is a stress distribution in the depth direction from the topmost surface of the Cr-plating layer to the substrate.

It is possible to calculate the depth-direction stress distribution of a thin layer which has texture, such as

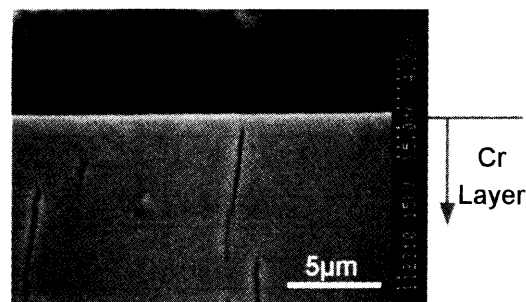


Fig.10. SEM micrographs of cross section of Cr-plating layer after postfinishing (sample D).

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the Cr-plating layer, by changing the wavelength of characteristic X-rays. For example, in the measurement of Cr {222} at $\psi_1=0\text{deg}$ and $\psi_2=70.5\text{deg}$ using characteristic Cu-K α X-rays, since the penetration depth is approximately 1/3 of the characteristic Cr-K α X-rays, evaluation of the stress distribution in the depth direction may be possible. We will examine the stress distribution in the depth direction in the future.

7. CONCLUSIONS

The mechanism of corrosion resistance degradation of Cr-plated parts due to heat treatment and measures to prevent such decrease were discussed and the following conclusions were reached.

- (1) When postfinishing is carried out after Cr-plating, the cracks in the Cr-plating layer are closed as a result of plastic flow on the topmost surface layer. When the residual stress in the Cr-plating layer becomes compressive, cracks are completely closed, resulting in high corrosion resistance of the layer.
- (2) The residual stress in the Cr-plating layer becomes more tensile upon heat treatment, and when the residual stress becomes tensile, the cracks in the Cr-plating layer, which are closed during postfinishing, open again, resulting in a decrease of corrosion resistance. It is considered that the change of residual stress to tensile stress is caused by (a) shrinkage of the Cr-plating layer upon heat treatment, (b) the difference in the coefficients of linear expansion between the Cr-plating layer and the substrate (steel) and (c) the relaxation of residual stress.

- (3) The application of compressive stress which exceeds the change in the residual stress towards tensile stress upon heat treatment to the Cr-plating layer in postfinishing was found to be effective in preventing the corrosion resistance degradation upon heat treatment.

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