

Electroplating of Chromium From Cr (III) Aqueous Solutions on the Mild Steel: Optimization of Bath Constituents

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Abstract – The investigation was aimed to electro deposit chromium on mild steel surface from non-toxic trivalent chromium bath instead of toxic hexavalent chromium employed for this purpose. The effects of bath constituents on the current efficiency, deposition rate, micro hardness, and optical reflectivity of Cr (III) plated mild steel were studied. The results revealed that the current efficiency and deposition rate increased linearly but micro hardness and optical reflectivity decreased gradually with the rise of chromium (III) chloride concentration. Completely reverse effects were observed when organic additive polyethylene glycol (PEG) and complexing agent (HCOOH) were added in to the plating bath. However, sodium sulfate produced a nonlinear relationship with current efficiency and hardness but the optical reflectivity decreased linearly with the increased of Na₂SO₄ concentration. SEM and EDX results showed smooth deposition of chromium when the bath contained lower amount of Cr³⁺.

Keywords – Electroplating, Current Efficiency, Optical Reflectivity, Complexing Agent, Organic Additive.

I. INTRODUCTION

The electroplating of chromium is extensively used commercially due to its unique and extraordinary properties such as low friction coefficient, exceptional wear resistance, outstanding corrosion resistance and also for its aesthetic appeal^[1,2]. Conventionally, chromium is deposited from hexavalent chromium bath as it offers better throwing power, bright surface finish, less porous deposition, good corrosion resistance and ease of deposition^[3,4]. Ironically, the toxic and carcinogenic nature of hexavalent chromium confronts worldwide environmental regulations, and its use is restricted now a days^[5]. Consequently, Cr(III) has been appeared as the most acceptable process to replace hexavalent chromium due to its low toxicity, and twice larger electrochemical equivalent^[6,7]. However, several complexities involved in chromium plating make the process unfavorable to commercial application. Firstly, Cr³⁺ is the most stable state of the element. In aqueous phase it forms kinetically inert octahedral complex called [Cr(H₂O)₆]³⁺ by d²sp³ hybridization that limits the electroreduction process^[8]. Secondly, the reduction potential of Cr³⁺ to Cr⁰ (E⁰ = -0.74V vs. SHE) is more negative than the reduction potential of water to hydrogen^[9].



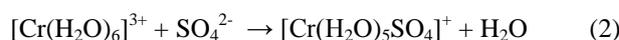
$$E^0 = -0.12\text{V vs. SHE (at pH 2)} \quad (1)$$

This indicates a considerable amount of hydrogen evolution for minimum Cr³⁺ reduction. In addition, reaction 1, as proceeds, causes a significant increase of pH at the cathode surface which leads the polymerization of [Cr(H₂O)₆]³⁺ to higher molecular weight compound. This precipitates near the surface and reduces the availability of Cr³⁺ for the desired reduction^[8-10]. Poor adhesion, excessive porosity and milky precipitate formation are also major difficulties of trivalent chromium plating.

In order to avoid the complexity of Cr³⁺ reduction, several complexing agents have been suggested in the literature^[1,5,7,11-13]. Protsenko and Danilov state that formic acid facilitates the formation of [Cr(H₂O)₄CHOO]²⁺ instead of [Cr(H₂O)₆]³⁺^[14]. The former having the structure of irregular octahedron with Cr³⁺ ion in the vortex can easily come to contact with the cathode surface to accept electrons.

Polyethylene glycol (PEG) has predominantly been used as a surfactant to improve the morphology and chemical properties in zinc, copper, chromium and zinc-chromium alloy plating^[11,15]. It has been reported that presence of PEG molecule in Cr(III) bath lowers the hydrogen evolution by adsorbing on the cathode surface, and allows a smooth, low crack and nodular type of deposit^[11]. On the contrary, Lee et al. have established that hydrogen evolution reaction is accelerated when PEG molecules adsorb on the cathode surface making the deposit more cracked^[5]. The authors also claim that PEG molecules promote the co-deposition of chromium and carbon in trivalent chromium plating system.

Sulfate ions, participating as a ligand for the Cr³⁺, substitute water molecules from the [Cr(H₂O)₆]³⁺ ion according to the following reaction^[9]



This indicates that gradual substitution of water with sulfate ions changes the nature of chromium complexes, and sulfate ions strongly influence the deposition process.

This investigation was aimed to electroplate Cr from Cr(III) aqueous solution containing sodium sulfate

(Na_2SO_4), polyethylene glycol (PEG), formic acid (HCOOH), formaldehyde (HCHO) and boric acid (H_3BO_3). Optimization of the bath concentration with respect to current efficiency, optical reflectivity and micro hardness was the primary goal.

II. EXPERIMENTAL

Commercial grade mild steel coupons having dimension $4 \text{ cm} \times 4 \text{ cm} \times 0.05 \text{ cm}$ were used as cathode for chromium plating. The coupons were polished successively with different grade of emery paper down to 1200 to obtain a mirror finish surface, washed thoroughly with liquid soap solution, degreased in acetone and finally rinsed in distilled water. The air dried specimen was insulated with synthetic paint leaving $1 \text{ cm} \times 1 \text{ cm}$ area exposed for experiment. The electroplating was carried out galvanostatically in an open glass beaker containing the electrolyte with mild steel coupon as cathode and platinum foil as anode connected to a controllable dc power source (GW Instek GPS 3030DD DC Power Supply, USA). The electrolyte for trivalent chromium plating was CrCl_3 as a source of trivalent chromium ion, HCOOH as a complexant, H_3BO_3 as a buffering agent, Na_2SO_4 as a mixed electrolyte system, and PEG as an organic additive. All chemicals used were analytical grade reagents procured from E. Merck, Germany and E. Merck India. After electroplating the coupon was rinsed with distilled water, air dried and finally dried at 80°C in an oven for 2 hours. Weight of the dry coupon before and after electroplating was measured using a digital analytical balance. The current efficiency and deposition rate of the deposit were calculated by weight gain method.

Optical reflectivity of the electroplated specimen was measured by UV-Visible spectrophotometer (model UV-1650PC, Shimadzu Corporation, Japan) within the wavelength range between 200 nm to 1100 nm. Model HVS-100 Digital Micro hardness Tester (Laryee Technology Co. Ltd., USA) with Vickers's micro hardness indenter was used for micro hardness measurement at a load 9.8 N for 10 sec. Morphological study of the Cr (III) plated specimen was made by Model FEI Quanta Inspect S50 Scanning Electron Microscope (SEM) (Japan). Energy Dispersive X-ray (EDX) facility of the SEM was used for the identification of the composition of the plated specimens.

III. RESULTS AND DISCUSSION

3.1 Effect of bath composition on current efficiency

The effect of different bath constituents on the current efficiency and deposition rate has been illustrated in Figures 1 to 4. Generally, the constituents have different influence on the current efficiency. As observe, current efficiency grows up with the rise of Cr^{3+} concentration (Figure 1).

A plateau like behavior is found at around 100 g/L to 120 g/L CrCl_3 concentration before a sharp proliferation of current efficiency. Figure 2 shows that the current efficiency surges with the addition of sodium sulfate

concentration up to 30 g/L. Afterwards, it dropped up to 60 g/L Na_2SO_4 , the highest concentration in this case.

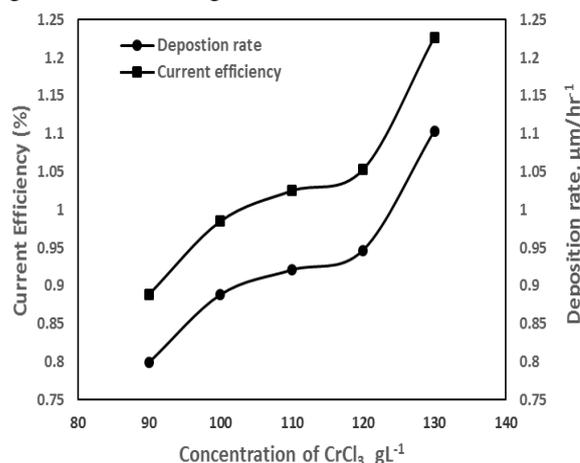


Fig.1. Current efficiency and deposition rate as a function of chromium (III) chloride concentration from the bath containing 40 g/L Na_2SO_4 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO and CrCl_3 . Operating conditions: current density 20 amp/dm^2 ; temperature 40°C and plating time 2 hours.

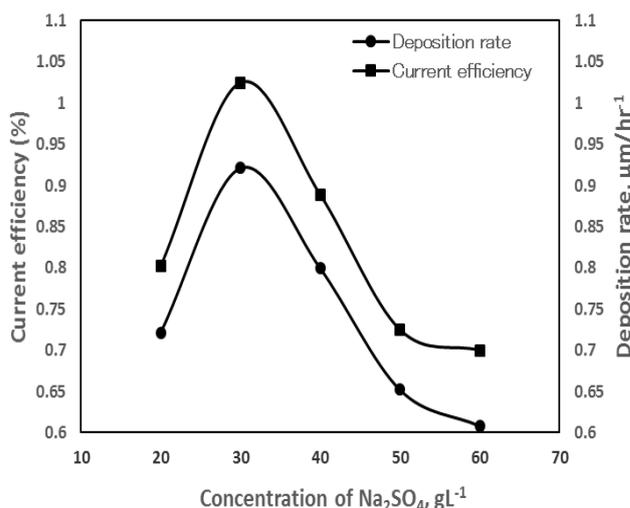


Fig.2. Current efficiency and deposition rate as a function of sodium sulfate concentration from the bath containing 110 g/L CrCl_3 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO and Na_2SO_4 . Operating conditions: Current density 20 amp/dm^2 ; temperature 40°C and plating time 2 hours.

Addition of PEG and HCOOH into the plating bath exhibits negative influence on current efficiency and deposition rate as both linearly decline with increase of the concentration of both (Fig. 3 & 4).

It should be noted that the deposition rate follows the same trend as current efficiency in all investigations indicating that current efficiency is directly related to the deposition of Cr.

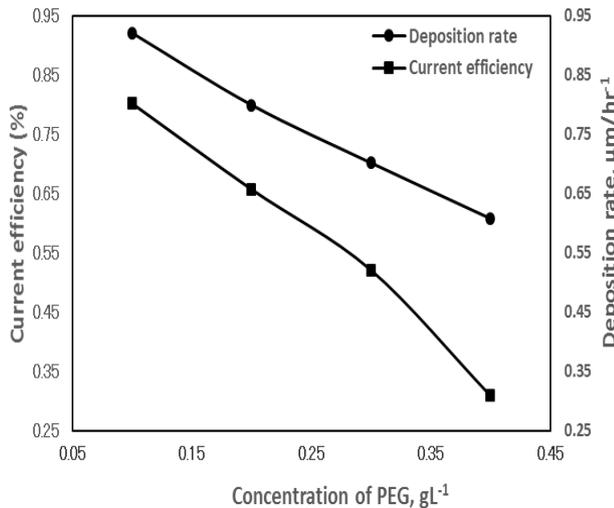


Fig.3. Effect of concentration of PEG on the current efficiency and deposition rate from the bath containing 110 g/L CrCl_3 , 40 g/L Na_2SO_4 , 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO and PEG. Operating conditions: current density 20 amp/ dm^2 ; temperature 40 °C and plating time 2 hours.

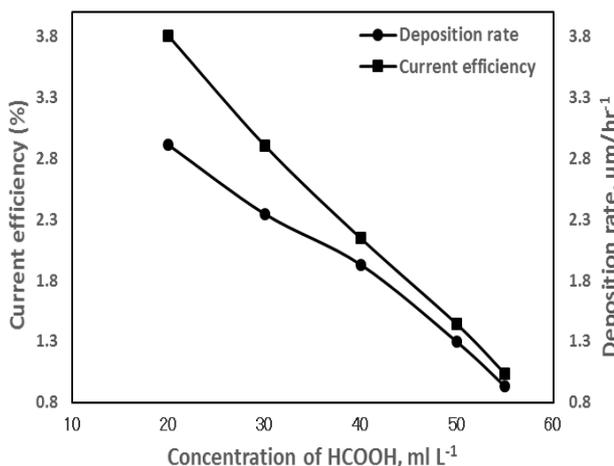


Fig.4. Current efficiency and deposition rate as a function of formic acid concentration from the bath containing 110 g/L CrCl_3 , 40 g/L Na_2SO_4 , 40 g/L H_3BO_3 , 0.1 g/l PEG, 4 ml/L HCHO and formic acid. Operating conditions: current density 20 amp/ dm^2 ; temperature 40 °C and plating time 2 hours.

3.2 Effect of bath composition on micro hardness of the deposit

Figures 5, 6 and 7 represent the micro hardness of deposited Cr at different concentration of CrCl_3 , Na_2SO_4 , and PEG respectively. It is evident that the hardness of deposits gradually decreased from 2653 HV to 1769 HV when the concentration of CrCl_3 grew up from 90 to 120 g/L. Then it dropped steeply to 410 HV at 130 g/L CrCl_3 .

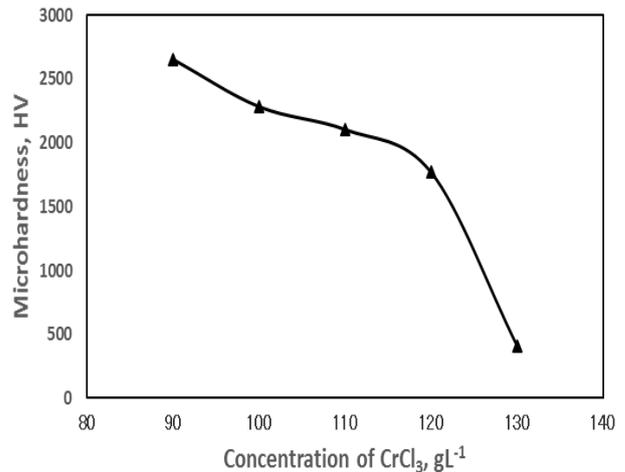


Fig.5. Hardness of Cr plated surface as a function of chromium (III) chloride concentration from the bath containing 40 g/L Na_2SO_4 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO and CrCl_3 . Operating conditions: current density 20 amp/ dm^2 ; temperature 40 °C and plating time 2 hours.

On the contrary, extending the concentration of PEG improved the hardness of the deposits gradually from 1610 to 2967 HV. In the case of addition of Na_2SO_4 concentration, hardness increased up to 40 g/L concentration and then reduced steeply.

3.3 Effect of bath composition on optical reflectivity of the deposit

Optical reflectivity is the measure of brightness and smoothness of the deposited surface. Optical reflectivity of the deposits at wavelength from 400 to 700 nm as a function of different bath constituent was shown in Figures 8 to 10. It is found from Figures 8 & 9 that lowest concentration of CrCl_3 and Na_2SO_4 produced maximum surface brightness.

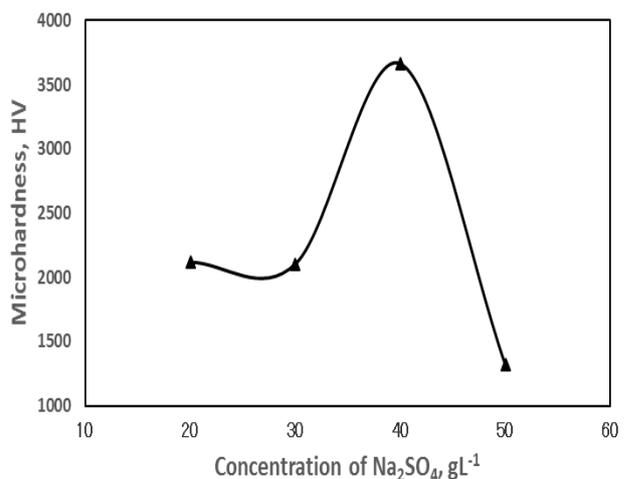


Fig.6. Hardness of plated surface as a function of Na_2SO_4 concentration from the bath containing 110 g/L CrCl_3 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO and Na_2SO_4 . Operating conditions: Current density 20 amp/ dm^2 ; temperature 40 °C and plating time 2 hours.

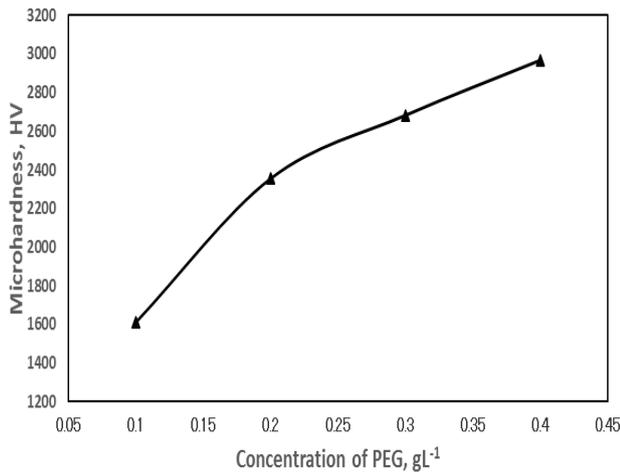


Fig.7. Hardness of plated surface as a function of PEG concentration from the bath containing 110 g/L $CrCl_3$, 40 g/L Na_2SO_4 , 40 g/L H_3BO_3 , 40 ml/L $HCOOH$, 4 ml/L $HCHO$ and PEG. Operating conditions: current density 20 amp/dm^2 ; temperature 40 °C and plating time 2 hours.

The surfaces became gradually darker as concentration of the both constituents increased. On the other hand, PEG concentration had a positive effect on the surface reflectivity for all concentrations (Figure10).

3.4 Characterization of Cr (III) deposit

The morphology and composition of the Cr (III) electroplated surface at low and high Cr^{3+} ions containing bath have been studied by SEM and EDX analysis. The SEM images were collected at 25 kV for approximately 11 mm of working distance using a secondary electron detector.

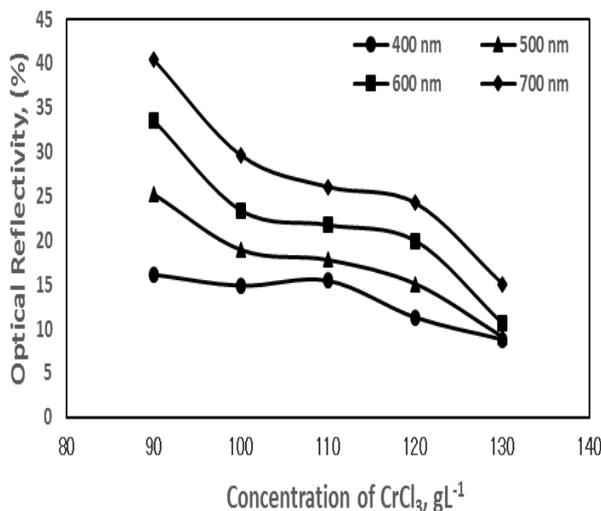


Fig.8. Optical reflectivity of plated surface as a function of chromium (III) chloride concentration from the bath containing 40 g/L Na_2SO_4 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L $HCOOH$, 4 ml/L $HCHO$ and $CrCl_3$. Operating conditions: current density 20 amp/dm^2 ; temperature 40 °C and plating time 2 hours.

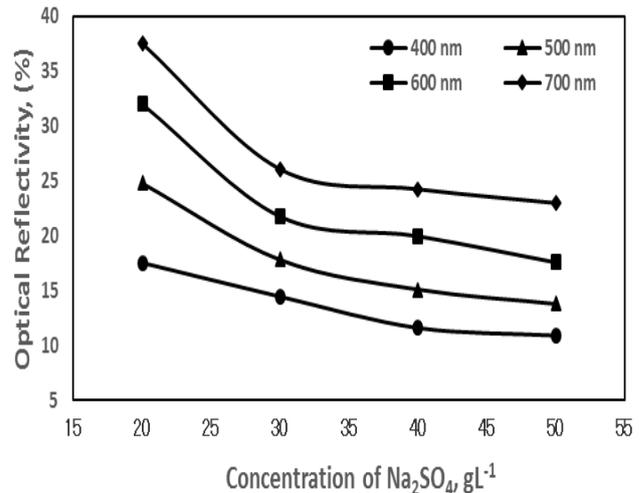


Fig.9. Optical reflectivity of plated surface as a function of Na_2SO_4 concentration from the bath containing 110 g/L $CrCl_3$, 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L $HCOOH$, 4 ml/L $HCHO$ and Na_2SO_4 . Operating conditions: Current density 20 amp/dm^2 ; temperature 40 °C and plating time 2 hours.

Bath having lower concentration of Cr^{3+} (90 g/L) produced a deposit of identical particle size with minor crack on the surface (Fig. 11).

The surface was mostly covered by deposited product and deposition was uniform. The results coincided with the findings obtained from optical reflectivity and hardness measurement as a better optical reflectivity and micro hardness were found at same condition due to the compactness, smoothness and homogeneity of the surface. EDX results confirmed the deposition of almost 75 wt % of Cr at this condition. On the contrary, at higher concentration Cr^{3+} ions (130 g/L) a cluster type of deposition was appeared making the surface irregular and non homogeneous as shows in Fig. 12.

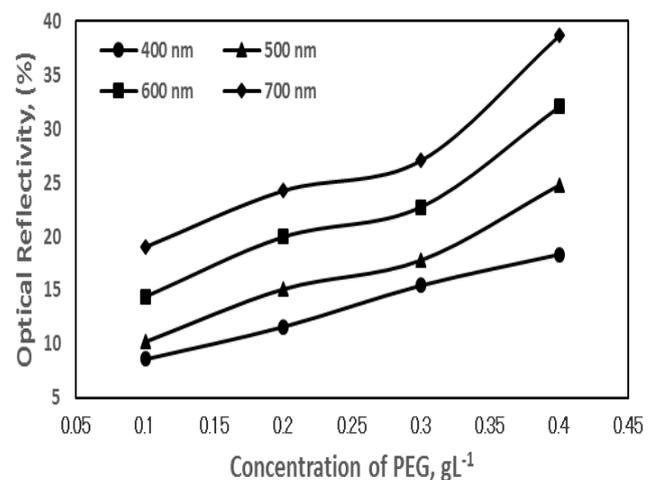


Fig.10. Optical reflectivity of plated surface as a function of PEG concentration from the bath containing 110 g/L $CrCl_3$, 40 g/L Na_2SO_4 , 40 g/L H_3BO_3 , 40 ml/L $HCOOH$, 4 ml/L $HCHO$ and PEG. Operating conditions: current density 20 amp/dm^2 ; temperature 40 °C and plating time 2 hours.

EDX revealed the presence of relatively higher amount of chromium (92 wt%) on the surface at this condition.

3.5 Discussion

We have observed an increase of current efficiency and deposition rate with the increase of CrCl_3 concentrations in the plating bath. This is due to the ease of availability of Cr^{3+} ions in the bath solution. According to the literature report, an increase of the concentration of metal salt usually causes the conductivity to approach a maximum for moderate ionic mobility enhancing the electrode position^[16]. A faster deposition rate due to the availability of Cr^{3+} in the solution has a tendency to make the deposition non-uniform. Optical reflectivity has direct relationship with the uniformity of plating. A uniform surface reflects maximum light making the surface bright. The micro hardness is also related to the uniformity of the deposition and also the grain size of the deposits.

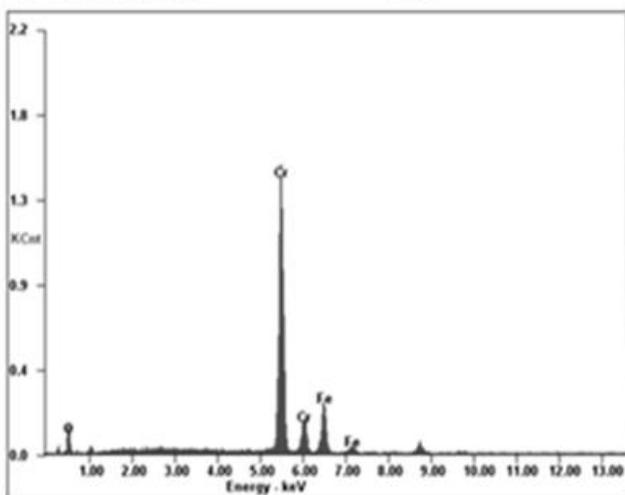
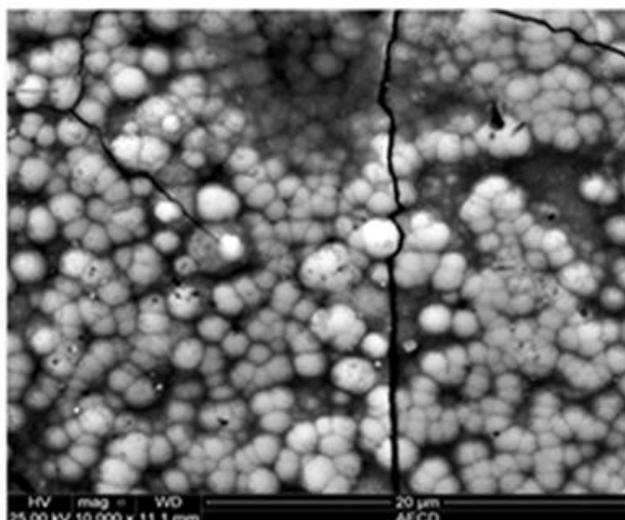


Fig. 11. SEM and EDX spectrum of chromium plated steel surface. Deposition was accomplished from a bath containing 90g/L CrCl_3 , 40 g/L Na_2SO_4 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , and 4 ml/L HCHO . Operating conditions: current density 20 amp/dm²; temperature 40 °C and plating time 2 hours.

It has been reported that the grain size, residual stress and inclusions of metallic and nonmetallic phases

remarkably influence the hardness of the chromium deposits^[17]. That is why the surface of the deposit gets darker with the increase of Cr^{3+} ions in the bath. The uniformity and small grain is also confirmed by the SEM image. It is clear that the particle size for the 90 g/L CrCl_3 is almost uniform and mostly covers the substrate. On the other hand, there is a formation of clusters and the surface loses uniformity due to the high deposition rate and higher amount of Cr^{3+} ion in the solution.

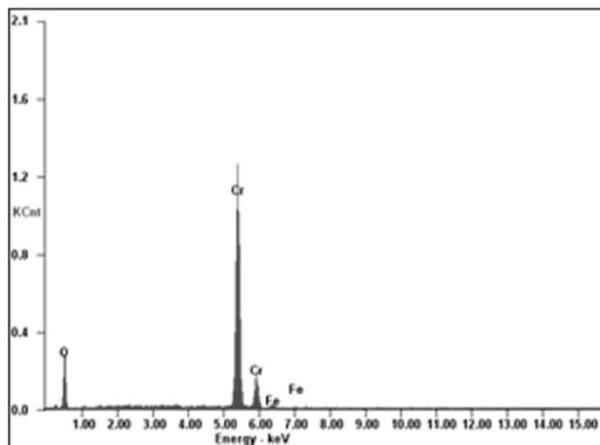
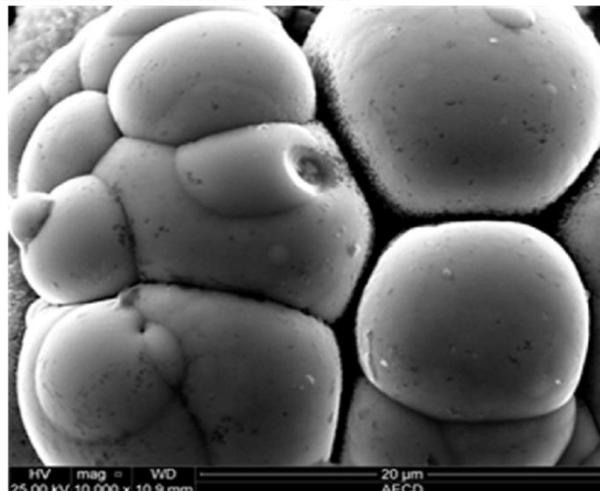


Fig. 12. SEM and EDX spectrum of chromium plated steel surface. Deposition was accomplished from a bath containing 130g/L CrCl_3 , 40 g/L Na_2SO_4 , 0.1 g/L PEG, 40 g/L H_3BO_3 , 40 ml/L HCOOH , 4 ml/L HCHO . Operating conditions: current density 20 amp/dm²; temperature 40 °C and plating time 2 hours.

The plating current efficiency and deposition rate accelerated with the increase of Na_2SO_4 concentrations up to 30 g/L and hardness raised up to 40 g/L, and afterwards both decreased up to 60 g/L. The main reason is that, SO_4^{2-} replaces the H_2O molecule according to reaction (2) as discussed earlier. Lower concentration of SO_4^{2-} formed complexes like $[\text{Cr}(\text{H}_2\text{O})_5\text{SO}_4]^+$ and the regular octahedron structure was disappeared and the deposition rate increased primarily. But, as the concentration of SO_4^{2-} exceeded a threshold (30 g/L), additional SO_4^{2-} replaced the H_2O molecule and the solvated complex gradually became $[\text{Cr}_2(\text{H}_2\text{O})(\text{SO}_4)_4]^{2-}$ to $[\text{Cr}_2(\text{SO}_4)_6]^{6-}$ ^[3]. Clearly, the complexes having the negative charged have a repelling action towards the cathode. Hence, less amount of Cr^{3+}

can reach the surface making the deposition non-uniform. So, the deposition rate, current efficiency, micro hardness and optical reflectivity fell down.

An increase of PEG concentration lowered both the current efficiency and deposition rate, while the hardness and optical reflectivity were improved. Alike many surfactants used in plating, PEG selectively adsorbed on the active sites during chromium plating. Therefore, deposition became favorable for less active sites^[12]. This also favors uniform and smoother chromium plating. Akiyama et al. explained that increase of PEG concentration in the electrolyte produced compact-deposit with finer grains^[15]. Similar type of findings was also confirmed by Lee et al.^[5] The overall effects are responsible for decreasing the current efficiency and deposition rate, and increasing of optical reflectivity and hardness.

The current efficiency and deposition rate of Cr(III) electrode position decreased with the increase of formic acid (HCOOH) concentration. Formic acid has been used as a complexing agent. As discussed earlier, formic acid also makes complexes of $[\text{Cr}(\text{H}_2\text{O})_5(\text{CHOO})]^{2+}$, instead of $[\text{Cr}(\text{H}_2\text{O})_6]^{3+}$ in the solution and ensures constant and regulated supply of Cr^{3+} ion on the cathode for better and improved plating quality. However, very strong bonding between the HCOOH and Cr^{3+} in $[\text{Cr}(\text{H}_2\text{O})_5(\text{HCOO})]^{2+}$ $[\text{Cr}(\text{H}_2\text{O})_4(\text{HCOO})]^{2+}$ make the reduction of Cr^{3+} difficult at the cathode surface^[9]. So, the rate of deposition decreased with the increase of HCOOH concentration.

Finally, it can be concluded that the current efficiency and deposition rate increased with CrCl_3 concentration but decreased with PEG and formic acid concentration. Additions of PEG and formic acid in the bath improved the surface brightness and micro hardness of the deposit whereas a reverse influence was observed with the increase of CrCl_3 concentration. A nonlinear effect of the Na_2SO_4 concentration on current efficiency and hardness of deposit was observed. Maximum efficiency and hardness were found at 30 and 40 g/L of Na_2SO_4 respectively. However, surface reflectivity decreased with the increase of Na_2SO_4 concentration. SEM confirmed more uniform deposition at low concentration of CrCl_3 compared to high concentration.

IV. CONCLUSION

1. The current efficiency and deposition rate are increased with CrCl_3 concentration but decreased with PEG and formic acid concentration.
2. Addition of PEG and formic acid in the bath improves the surface brightness and micro hardness of the deposit whereas a reverse effect is observed with increase of CrCl_3 concentration.
3. A nonlinear effect of Na_2SO_4 on current efficiency and hardness of deposit is observed. Maximum efficiency and hardness are found at 30 and 40 g/L respectively. However, surface reflectivity gets down with the increase of Na_2SO_4 concentration.
4. SEM confirms more uniform deposition at low concentration of CrCl_3 compare to high concentration.

REFERENCES

- [1] Protsenko, V.S., Danilov, F. I., Gordiienko, V.O., Kwon, S.C., Kim, M. and Lee, J.Y., "Electrode position of hard nanocrystalline chrome from aqueous sulfate trivalent chromium bath," *Thin Solid Films*, 520(1), 380–383, 2011.
- [2] Protsenko, V., Gordiienko, V., Butyrina, T., Vasil'Eva, E. and Danilov, F., "Hard chromium electrode position from a trivalent chromium bath containing water-soluble polymer," *Turkish J. Chem.*, 38, 50–55, 2014.
- [3] Protsenko, V.S., Gordiienko, V.O., Danilov, F.I. and Kwon, S.C., "Preparation and Characterization of Nanocrystalline Hard Chromium Coatings Using Eco-Friendly Trivalent Chromium Bath," *E-Journal Chem.*, 8(4), 1925–1929, 2011.
- [4] Weiner, I. and Walmsley, A., *Chromium Plating*. Middlesex, England: Finishing Publications Ltd., pp.47, 1980.
- [5] Lee, J.-Y., Kim, M. and Kwon, S.-C., "Effect of polyethylene glycol on electrochemically deposited trivalent chromium layers," *Trans. Nonferrous Met. Soc. China*, 19(4), 819–823, Aug. 2009.
- [6] Baral, A., Engelken, R., Stephens, W., Farris, J. and Hannigan, R., "Evaluation of Aquatic Toxicities of Chromium and Chromium-Containing Effluents in Reference to Chromium Electroplating Industries," *Arch. Environ. Contam. Toxicol.*, 50, 496–502, 2006.
- [7] Song, Y. and Chin, D., "Current efficiency and polarization behavior of trivalent chromium electrode position process," *Electrochim. Acta*, 48, 349–356, 2002.
- [8] Mandich, N., "Chemistry & theory of chromium deposition: part I-chemistry," *Plat. Surf. Finish*, 84(5), 108–115, 1997.
- [9] Giovanardi, R. and Orlando, G., "Chromium electrodeposition from Cr(III) aqueous solutions," *Surf. Coatings Technol.*, 205(15), 3947–3955, Apr. 2011.
- [10] Saravanan G. and Mohan, S., "Structure, current efficiency, and corrosion properties of brush electrodeposited (BED) Cr from Cr(III)dimethyl formamide (DMF)-bath," *J. Appl. Electrochem.*, 40(1), 1–6, Jun. 2009.
- [11] Van Phuong, N., Kwon, S.C., Lee, J.Y., Lee, J.H. and Lee, K.H., "The effects of pH and polyethylene glycol on the Cr(III) solution chemistry and electrode position of chromium," *Surf. Coatings Technol.*, 206(21), 4349–4355, Jun. 2012.
- [12] Van Phuong, N., Kwon, S.-C., Lee, J.-Y., Shin, J., Huy, B.T. and Lee, Y.-I., "Mechanistic study on the effect of PEG molecules in a trivalent chromium electrode position process," *Microchem. J.*, 99(1), 7–14, Sep. 2011.
- [13] Protsenko, B.Y., Gordiienko, V.O., Danilov, F.I. and Kwon, S.C., "Thick chromium electrode position from trivalent chromium bath containing carbamide and formic acid: An investigation into current efficiency, electrode position rate and surface morphology," *Met. Finish.*, 109(4–5), 33–37, 2011.
- [14] Protsenko V. and Danilov, F., "Kinetics and mechanism of chromium electrode position from format and oxalate solutions of Cr(III) compounds," *Electrochim. Acta*, 54(24), 5666–5672, Oct. 2009.
- [15] Akiyama, T., Kobayashi, S., Ki, J., Ohgai, T. and Fukushima, H., "Role of polyethylene glycol in electrodeposition of zinc-chromium alloys," *J. Appl. Electrochem.*, 30, 817–822, 2000.
- [16] Lowenheim, F.A., "Modern Electroplating," 2nd Edition. New York: John Willey and Sons Inc., pp. 176, 1963.
- [17] Danilov, F.I., Protsenko, V.S., Gordiienko, V.O., Kwon, S.C., Lee, J.Y. and Kim, M., "Nanocrystalline hard chromium electrode position from trivalent chromium bath containing carbamide and formic acid: Structure, composition, electrochemical corrosion behavior, hardness and wear characteristics of deposits," *Appl. Surf. Sci.*, 257(18), 8048–8053, Jul. 2011.



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