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Figure 1

DES (Current density mA cm ⁻²)	Optical image	SEM image	Cross section thickness	Hardness/ HV
2urea:CrCl ₃ : 6H ₂ O (200)				650 ± 10
DES + 20% H ₂ O (122)				715 ± 10
DES + 0.1 M boric acid (250)				610 ± 10
DES + 0.1 M NaBr (250)				600 ± 10
DES + 20% H ₂ O + 0.1 M boric acid (150)				850 ± 10
DES + 20% H ₂ O + 0.1 M NaBr (180)				700 ± 10

(57) Abstract: There is provided an electrolyte for the electrodeposition of chromium comprising: (A) water; (B) at least one chromium salt; and (C) at least one complexing agent, wherein the molar ratio of components B:C is in the range of 1 :1 to 1 :50. There is also provided a method for electrodepositing chromium metal onto a conductive substrate.



Electrolyte for Electroplating

This invention relates to the use of ionic liquids in electroplating, and in particular for
5 electroplating thick, hard chromium from trivalent salts.

Electroplating is an electrodeposition process for producing a thick, uniform, and adherent
coating, commonly of metal or alloys, upon a surface by the act of electric current (see, M.
Kulkarni *et al*, *Bangladesh Journal of Scientific and Industrial Research*, 2013, 48, 205-
10 212). The coating formed changes the properties of the underlying substrate and is
generally applied to improve wear and corrosion resistance of the interface or improve the
aesthetic properties of the object. The piece to be electroplated is made into the negative
electrode in an electrochemical cell and a current is passed through an electrolyte
containing the ions of the metal to be electrodeposited.

15

There has been little change in the method of electroplating over 100 years and almost all
processes are based on aqueous solutions of metal salts with a variety of additives to
control morphology and properties. The industry is dominated by a relatively small number
of coating materials. Anti-wear coatings are mostly Cr, Ni and Co and their alloys with other
20 metals (M. Schlesinger and M. Paunovic, *Modern Electroplating*, John Wiley & Sons, 2010;
and Z. Zeng and J. Zhang, *Journal of Physics D: Applied Physics*, 2008, 41, 185303).

The use of aqueous solutions has many issues for electroplating primarily due to the
narrow potential window, and so metals with a large negative reduction potentials, e.g. Cr
25 and Zn, are deposited with poor current efficiencies and suffer from hydrogen
embrittlement (A. P. Abbott and K. J. McKenzie, *Physical chemistry chemical physics* :
2006, 8, 4265-4279).

Furthermore, although water is a green solvent, the inclusion of high metal concentrations
30 means that the water has to be extensively cleaned before it can be returned to the
environment (R. D. Rogers, K. R. Seddon, A. C. S. Meeting, *Ionic Liquids As Green
Solvents: Progress and Prospects*, American Chemical Society, 2003). The electroplating
process is also a complex series of pre-and post-treatment steps to prepare the substrate
and remove the electrolyte after coating.

35

There are a number of key advantages of using aqueous solutions, such as:

- Low cost
- Non-flammable
- High solubility of electrolytes
- 5 • High conductivities resulting in low ohmic losses and good throwing power
- High solubility of metal salts
- High rates of mass transfer

For these reasons, water will remain the backbone of the metal plating industry.

10 Nevertheless, there are also limitations of aqueous solutions comprising:

- Limited potential windows
- Gas evolution processes can be technically not easy to handle and results in hydrogen embrittlement
- 15 • Passivation of metals can cause issues with both anodic and cathodic materials
- Requirement for complexing agents such as cyanide
- All water must be returned to the water course

20 These issues stop aqueous solutions being useful to the deposition of several technically vital materials. The main research areas in electroplating include replacement of environmentally toxic metal coatings (such as chromium), deposition of novel alloys and semiconductors and new coating methods for reactive metals.

25 Chromium plays an important role in a number of modern industries, for example, as a protective material in automotive and aerospace applications as well as for decorative purposes. It has almost unparalleled hardness and is used extensively for hydraulic systems. Chromium is traditionally electroplated from chromic acid which is a mixture of CrO_3 and H_2SO_4 . Although this has been the basis of a successful technology for over 50 years it is highly toxic and carcinogenic. There has been cumulative anxiety due to
30 environmental, health and safety concerns related with the emission, treatment, storage which has led to reduced usage of hexavalent chromium compounds (K. Legg, M. Graham, P. Chang, F. Rastagar, A. Gonzales and B. Sartwell, *Surface and Coatings Technology*, 1996, 81, 99-105).

35 In general, hexavalent chromium electroplating baths produce trivalent chromium ions and hydrogen gas at the cathode, whereas oxygen gas is the major product at the anode.

Hexavalent chromium is strongly linked with lung cancer and it also causes burns, ulceration of the skin and the mucous membrane, and loss of respiratory sensation.

In addition to its toxicity there are other issues associated with the deposition of chromium from chromic acid electrolytes. These have been summarized by Smart *et al* (*Trans. Inst. Met. Finish.*, 1983, 61, 105-110) as follows:

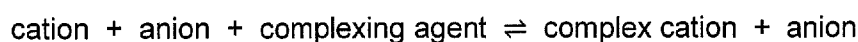
- Chromium electrodeposition utilising Cr(VI) has a low efficiency i.e. 15–22 % where the remainder of the applied current is used in hydrogen evolution.
- 10 • The average cathodic current densities are high (typically 10-15 Adm⁻²).
- The procedure has poor covering power across low current density areas.
- Burning is observed as grey deposits in high current density zones.
- Chromium electroplating has low throwing power, which results in thick electrodeposits on the boundaries and protruding parts of cathodes and thin deposits over
15 the rest of the surface.
- Breaks in power during electrodeposition produces milky deposits known as white washing.
- Chromic acid pose instant harmful effects on human tissue, burning the skin and even dilute solutions cause ulcers.
- 20 • Chromic acid is a strong oxidizing agent and hence is a fire hazard.
- High cost of chemical treatment.

Numerous studies have attempted to develop trivalent chromium formulations for chromium plating and while several have been commercialised they are all used for decorative coatings. Trivalent chromium is at least 100 times less toxic to humans and the
25 environment than hexavalent. Thermal spray techniques, nickel-based coatings and trivalent chromium electroplating have all been used as alternatives to Cr(VI) but none have comparable hardness.

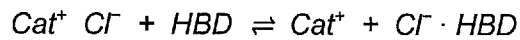
30 The Applicants have discovered ionic liquids which can be used to replace the typically used aqueous solutions and overcome the above identified problems. Ionic liquids can be expressed by the following equilibria;



35 or potentially:



- Type III Deep Eutectic Solvents are types of ionic liquids which do not include metallic species in the bulk liquid but use a hydrogen bond donor (HBD), such as urea or ethylene glycol to complex the anion from the salt (see, for example, Abbott *et al.* Novel solvent properties of choline chloride/urea mixtures. *Chem. Comm.*, 70, 2003; and Abbott *et al.* Deep Eutectic solvents formed between choline chloride and carboxylic acids, *J. Am. Chem. Soc.*, 26: 9142, 2004).



- 10 Deep Eutectic Solvents (DES) can be used in electroplating processes. They are simple to prepare, are insensitive to water content and do not need to be registered as their toxicological properties are known. Most importantly, for large scale applications like electroplating they are inexpensive. DES comprise of quaternary ammonium salts (e.g. choline chloride, ChCl), metal salts or metal salt hydrates and hydrogen bond donors (e.g. urea) and are commonly divided into four groups:
- 15
- (i) metal salt + organic salt
 - (ii) metal salt hydrate + organic salt
 - (iii) organic salt + hydrogen bond donor
 - 20 (iv) metal salt hydrate + hydrogen bond donor.

Wherein (i) describes Type I DES, (ii) describes Type II DES, (iii) describes Type III DES and (iv) describes Type IV DES.

- 25 Preferably, wherein Type I DES is a quaternary ammonium salt + metal chloride; Type II DES is a quaternary ammonium salt + metal chloride hydrate; Type III DES is a quaternary ammonium salt + hydrogen bond donor; and Type IV is a metal chloride hydrate + hydrogen bond donor.
- 30 Based on the above mentioned ionic liquids, the Applicants have surprisingly discovered an improved electrolyte for the electrodeposition of thick, hard chromium to circumvent the issues which occur when using hexavalent chromium (Cr(VI)).

- According to the present invention, there is provided an electrolyte for the electrodeposition of chromium comprising:

- (A) water;
- (B) at least one chromium salt; and

(C) at least one complexing agent,

wherein the molar ratio of components B:C is in the range of 1:1 to 1:50.

Preferably, the chromium salt is selected from at least one of $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$,
5 $\text{KCr}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ and $\text{Cr}_2(\text{SO}_4)_3 \cdot 10 \text{H}_2\text{O}$.

Optionally, the complexing agent is selected from acetamide, urea, ethylene glycol, 1,3-
propanediol, 1,4-butanediol, 1,5-pentanediol, 1,6-hexanediol or glycerol.

10 Preferably, the complexing agent is a quaternary ammonium halide, preferably wherein
the complexing agent is choline chloride.

Optionally, the electrolyte further comprises an additive selected from at least one of boric
acid, lactic acid, citric acid, ethylene diamine, sodium borate, sodium citrate, sodium
15 phosphate, nicotinic acid, dimethyl hydantoin and methyl nicotinate. Preferably, the
concentration of the additive is in the range of from 0.05 to 0.5 mol dm^{-3} .

Optionally, the electrolyte further comprises at least one bromide or iodide salt, preferably
wherein the salt is sodium iodide or lithium iodide. Preferably, wherein the salt is present
20 is in a concentration of from 0.05 to 0.2 mol dm^{-3} .

Preferably, wherein the electrolyte comprises less than 50% water, preferably from 10 to
25 wt% water.

25 In accordance with a further aspect of the present invention, there is provided a method of
electrodepositing chromium metal onto a conductive substrate comprising the steps of:

(i) contacting the substrate and a counter electrode with the electrolyte as defined
herein; and

(ii) passing a current through the electrolyte to electrodeposit the chromium onto the
30 substrate.

Preferably, the conductive substrate is selected from mild steel, copper, aluminium,
stainless steel, brass, cobalt or alloys thereof.

35 Optionally, the current density is in the range 50 to 300 mAcm^{-2} .

Preferably, the electrodeposition is carried out at a temperature of between 30 and 60°C .

According to the present invention, the cathode is moved through the electrolyte during the electrodeposition process either by:

- (i) rotation, wherein the rotation frequencies are in the range 0.1 to 10 Hz; or
- 5 (ii) horizontal motion, wherein the oscillation frequencies are in the range 0.1 to 10 Hz.

Preferably, the chromium deposited has a thickness of between 5 to 500 μm . Optionally, the chromium deposited has a hardness of > 600 HV.

- 10 According to a further aspect of the present invention, there is provided an electroplated product comprising a conductive substrate which has been electroplated according to a method disclosed herein.

According to the present invention, there are provided electrolytes for the electrodeposition
15 of thick, hard, chromium to circumvent the issues of using Cr(VI), to improve current efficiency and optimise the hardness and aesthetic finish of the deposit. While aqueous trivalent chromium solutions have previously been used, the deposits are usually thin (< 3 μm). The present invention allows thick deposits of chromium to be formed on a substrate. Preferably, wherein the chromium has a thickness of from 5 to 500 μm .

20

The deposits are also hard. When using the Vickers hardness test, the chromium has a hardness >600 HV (wherein HV is the Vickers Pyramid Number). The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces
25 subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds.

The Applicants have found that by using the electrolyte according to the present invention, amorphous crack-free chromium deposits were obtained. The black coatings produced had a similar appearance to 'Black Chrome' coatings produced from sulfate-free
30 hexavalent aqueous solutions. Furthermore, the coating thicknesses were greater than those obtained from aqueous baths.

In a preferred embodiment, the electrolyte comprises three components; water, a chromium salt and a complexing agent. Additional additives can optionally be used to
35 improve brightness, adhesion and process operating conditions.

Component A: Water is the minor component (by mass) but plays the role of controlling speciation of the chromium complex. While chromium can be deposited in the absence of water the optimum morphology and hardness are obtained with between 10 and 25 wt% water, preferably with 20% water. The water controls the chromium salt speciation and cationic metal complexes are important. Mass transport to and from the electrode surface is vital and water controls the viscosity of the liquid.

Component B: Is a chromium salt. Preferably the chromium salt is selected from $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$, $\text{KCr}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ and $\text{Cr}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$.

Component C: This component is a complexing agent which interacts with the chromium salt affecting speciation. The complexing agent can be an amide, such as urea or acetamide, a glycol such as glycerol or a quaternary ammonium halide such as choline chloride. Preferably, Component C is in molar excess of Component B.

Preferably, the molar ratio of **Component B: C** should optimally be in the range 1:1 to 1:50, preferably 1:1.5 to 1.3.

The electrolyte can optionally comprise additives, which are common in metal plating systems and can modify mass transport, speciation or adsorption at the electrode surface. Preferably, the additives are selected from those which improve deposit morphology, by adsorbing at the electrode/solution interface. Preferably, the additive is selected from at least one of boric acid, lactic acid, citric acid, ethylene diamine, sodium borate, sodium citrate, sodium phosphate, nicotinic acid, dimethyl hydantoin and methyl nicotinate. The optimum concentration for these additives is in the range 0.05 to 0.5 mol dm^{-3} .

In the absence of additives the anodic reaction on a dimensionally stable anode will be a mixture of oxygen evolution (from decomposition of water) and chlorine evolution from the oxidation of chloride. The latter is clearly undesirable due to its toxicity and the large overpotential required to drive the reaction at a suitable rate to support metal deposition at the cathode. To circumvent these issues bromide or iodide salts with cations can be added in the concentration range 0.05 to 0.2 mol dm^{-3} . Preferably, wherein the salt is sodium iodide, sodium chloride or lithium iodide.

The anodic products Br_2Cl^- and I_2Cl^- are soluble in the liquid due to the high ionic strength. The lower overpotential required to oxidise bromide or iodide, decreases the deposition potential and increase the current density that can be achieved. Incorporation of chromium

metal in the form of lumps or coarse powder close to the anode will allow the Br_2Cl^- or I_2Cl^- to oxidise the metal and maintain a roughly constant chromium content in the electroplating electrolyte. The role of additives in controlling morphology can be seen clearly in Figures 1 and 2.

5

Figure 1 shows an optical photograph, SEM image, thickness cross section and plating conditions of chromium deposit obtained from the electroreduction of 2 urea: $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ with and without additives, for 1 hour at 40 °C and 4-5 V.

10 **Figure 2** shows an optical photograph, SEM image, thickness cross section and plating conditions of chromium deposit obtained from the electroreduction of 2 urea: $\text{KCr}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ with and without additives, for 1 hour at 40 °C and 4-5 V.

15 **Figure 3** shows the effect of current density and potential pulse sequences on deposit morphology.

Figure 4 shows the effect of current density on deposit morphology obtained in a flow cell with a flow rate of 72.2 cm^3/s .

20 **Figure 5** shows the effect of current density on the deposit morphology obtained using the flow cell with a flow rate of 72.2 cm^3/s using chrome alum:urea:water based eutectic.

The optimum current density is in the range 50 to 300 mAcm^{-2} .

25 The temperature can affect speciation and mass transport. The temperature at which the above-described electrodeposition methods are conducted may be, for example, any temperature between 20 and 60°C. The optimum temperature is between 30 and 60°C.

30 Mass transport is vital in controlling morphology and optimum hardness and appearance are obtained when the cathode is moved through the electrolyte during the electrodeposition process. Movement is controlled by rotation (where rotation frequencies are in the range 0.1 to 10 Hz) or horizontal motion (where oscillation frequencies are in the range 0.1 to 10 Hz). This replenishes the electrolyte close to the electrode surface.

35 In relation to the above-described electrodeposition method, the conductive substrate may be any suitable solid, conductive material such as mild steel, copper, aluminium, stainless steel, brass, cobalt or alloys thereof.

Further, the reducing potential applied to the conductive substrate may be, for example, a constant potential. Alternatively, the deposition can be achieved by utilising a constant current. The current density is calculated based on the size of the substrate which is being
5 plated.

In particular embodiments of the invention, the electrodeposition in the above-described methods is conducted under an inert atmosphere (e.g. under an atmosphere of argon or, particularly nitrogen).
10

In a preferred embodiment, the electrolyte comprises 20 wt% water $1\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ and 2ChCl .

As discussed above, deposit morphology can be significantly affected by mass transport.
15 By mechanically moving the sample in the solution this provides better deposit morphology and improved hardness.

In an experiment, the plating was conducted from 40 litres volume of Chromline 50 (20 % H_2O w/w) with 0.1 M NaBr and 0.1 M H_3BO_3 . The conditions were as follows:

- 20
- One cathode – mild steel plate (1 mm thickness for all samples)
 - Two anodes – IrO_2 coated Ti mesh (Electrode area = 1056 cm^2), anode/cathode distance was 13 cm
 - Bath temperature was at $40 (\pm 3) ^\circ\text{C}$
 - Plated sample was moved laterally at ca. 0.5 Hz frequency

25 Examples of deposits obtained by this process are shown in Figure 3. Pulsing the applied potential also affected the deposit morphology as shown in Figure 3.

A flow cell can also improve deposit morphology and thickness at lower current densities, as shown in Figure 4.

30

In a further experiment, the plating was conducted from 11.8 litres volume of Chromline 50 (20 % H_2O w/w) in a flow cell. The conditions were as follows:

- 35
- One cathode – mild steel plate (1 mm thickness for all samples)
 - One anode – IrO_2 coated Ti mesh (EA $35 = \text{cm}^2$), anode/cathode distance set at 3.6 cm
 - Reaction temperature was controlled at $38 (\pm 4) ^\circ\text{C}$
 - Voltage was at $15 (\pm 4) \text{ V}$ but lower current densities were required

- Flow rate was at 72.2 cm³/s

The adhesion of the chromium layer onto a mild steel substrate can also be dependent upon the pre-treatment protocol. A suitable protocol to achieve effective degreasing
5 involves the following process.

- Degrease for 1 minute in hexane at room temperature with stirring
- Degrease for 10 minutes in Anapol C with stirring at 60 °C
- Rinse with water
- Rinse with acetone
- 10 • Dry with compressed air

The use of chrome alum based liquids with water produces coatings with less cracks and a harder surface (see Figure 5). In a further experiment, the plating was conducted from 0.3 litres volume of chrome alum/urea DES with 30% weight water. The conditions were
15 as follows:

- One cathode – mild steel plate (1 mm thickness for all samples)
- One anode – IrO₂ coated Ti mesh (area = 4 cm²), anode/cathode distance was 2.5 (±0.2)cm
- Reaction temperature was controlled at 17 (±2) °C
- 20 • Carried out in the same cell flow cell as discussed above.

CLAIMS

1. An electrolyte for the electrodeposition of chromium comprising:
 - (A) water;
 - 5 (B) at least one chromium salt; and
 - (C) at least one complexing agent,wherein the molar ratio of components B:C is in the range of 1:1 to 1:50.
2. The electrolyte according to claim 1, wherein the chromium salt is selected from at
10 least one of $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$, $\text{KCr}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ and $\text{Cr}_2(\text{SO}_4)_3 \cdot 10 \text{H}_2\text{O}$.
3. The electrolyte according to claim 1 or claim 2 wherein the complexing agent is
selected from acetamide, urea, ethylene glycol, 1,3-propanediol, 1,4-butanediol, 1,5-
pentanediol, 1,6-hexanediol or glycerol.
15
4. The electrolyte according to claim 1 or claim 2 wherein the complexing agent is a
quaternary ammonium halide, preferably wherein the complexing agent is choline chloride.
5. The electrolyte according to any preceding claim further comprising an additive
20 selected from at least one of boric acid, lactic acid, citric acid, ethylene diamine, sodium
borate, sodium citrate, sodium phosphate, nicotinic acid, dimethyl hydantoin and methyl
nicotinate.
6. The electrolyte according to claim 5 wherein the concentration of the additive is in
25 the range of from 0.05 to 0.5 mol dm⁻³.
7. The electrolyte according to any preceding claim further comprising at least one
bromide or iodide salt, preferably wherein the salt is sodium iodide, sodium chloride or
lithium iodide.
30
8. The electrolyte according to claim 7 wherein the salt is present is in a concentration
of from 0.05 to 0.2 mol dm⁻³.
9. The electrolyte according to any preceding claim wherein the electrolyte comprises
35 less than 50% water, preferably from 10 to 25 wt% water.

10. A method of electrodepositing chromium metal onto a conductive substrate comprising the steps of:

- (i) contacting the substrate and a counter electrode with the electrolyte as defined in any one of claims 1 to 9; and
- 5 (ii) passing a current through the electrolyte to electrodeposit the chromium onto the substrate.

11. The method according to claim 10 wherein the conductive substrate is selected from mild steel, copper, aluminium, stainless steel, brass, cobalt or alloys thereof.

10

12. The method according to claims 10 or 11 wherein the current density is in the range 50 to 300 mAcm⁻².

15

13. The method according to claims 10 to 12 wherein the electrodeposition is carried out at a temperature of between 30 and 60°C.

14. The method according to any one of claims 10 to 13 wherein the cathode is moved through the electrolyte during the electrodeposition process either by

20

- (i) rotation, wherein the rotation frequencies are in the range 0.1 to 10 Hz; or
- (ii) horizontal motion, wherein the oscillation frequencies are in the range 0.1 to 10 Hz.

15. The method according to any one of claims 10 to 14 wherein the chromium deposited has a thickness of between 5 to 500 µm.

25

16. The method according to any one of claims 10 to 15 wherein the chromium deposited has a hardness of > 600 HV.

17. An electroplated product comprising a conductive substrate which has been electroplated according to a method according to any one of claims 9 to 16.

30

35

Figure 1

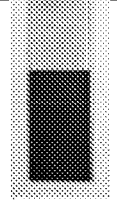
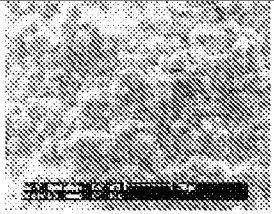
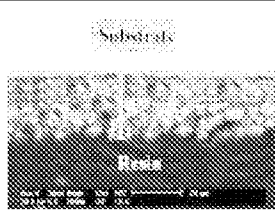
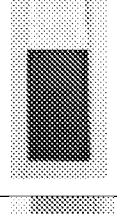
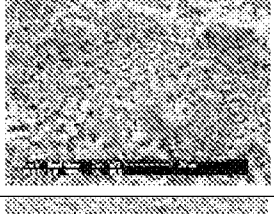
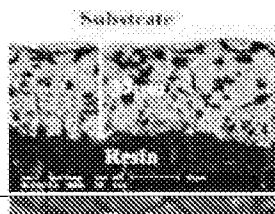
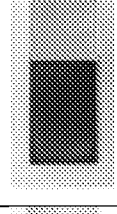

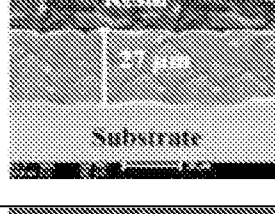
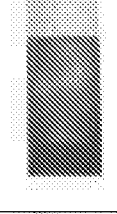


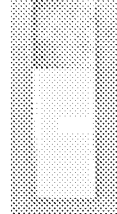
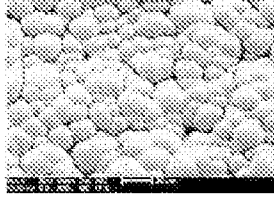
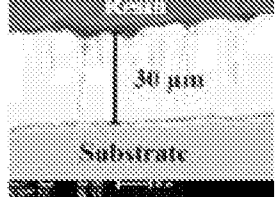
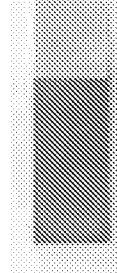
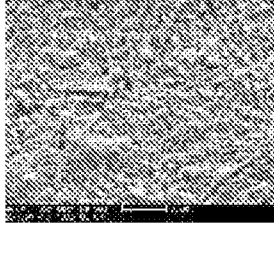
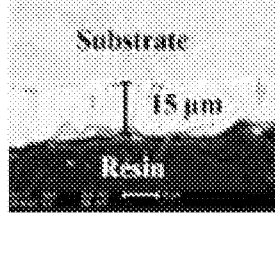
<i>DES + (Current density/ mA·cm⁻²)</i>	<i>Optical image</i>	<i>SEM image</i>	<i>Cross section thickness</i>	<i>Hardness/ HV</i>
2urea:CrCl ₃ · 6H ₂ O (200)				650± 10
DES + 20% H ₂ O (122)				715 ± 10
DES + 0.1 M boric acid (250)				610 ± 10
DES + 0.1 M NaBr (250)				600 ± 10
DES + 20% H ₂ O + 0.1 M boric acid (150)				850+10
DES + 20% H ₂ O + 0.1 M NaBr (180)				700 ± 10

Figure 2

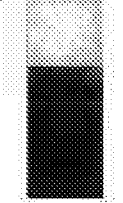
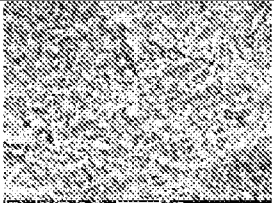
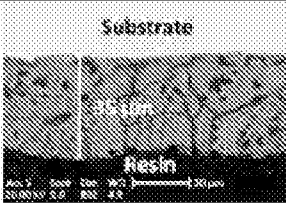
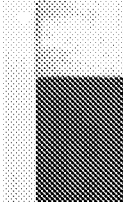
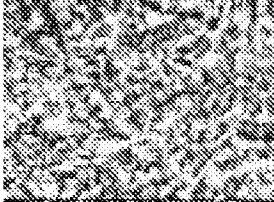
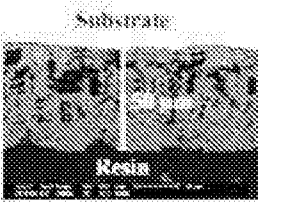
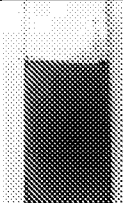
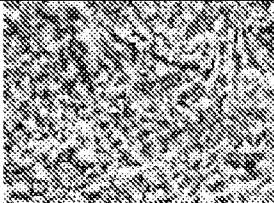
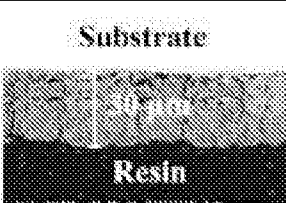
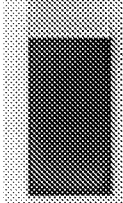
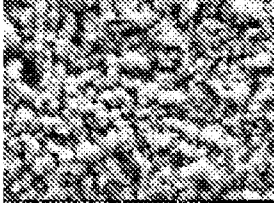
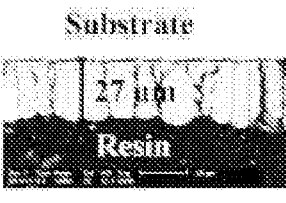
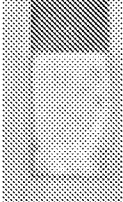

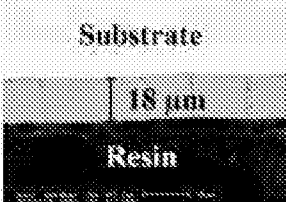
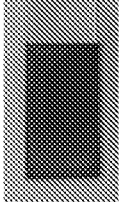
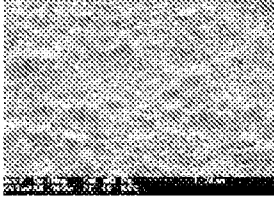

DES + (Current density/ $mAc m^{-2}$)	Optical image	SEM image	Cross section thickness	Hardness/ HV
2urea: $KCr(SO_4)_2 \cdot 12 H_2O$ (150)				680 ± 10
DES + 20% H_2O (125)				700 ± 10
DES + 0.1 M boric acid (150)				680 ± 10
DES + 0.1 M NaBr (150)				650 ± 10
DES + 20% H_2O + 0.1 M boric acid (130)				800 ± 10
DES + 20% H_2O + 0.1 M NaBr (120)				780 ± 10

Figure 3


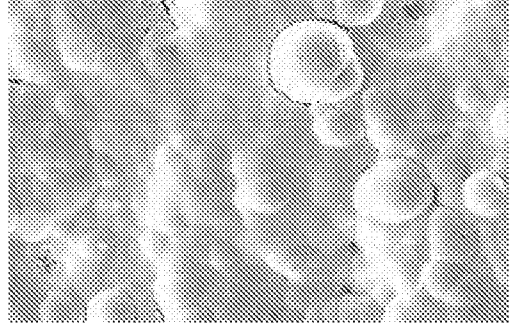
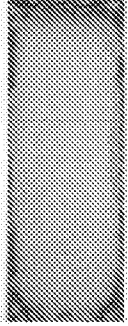
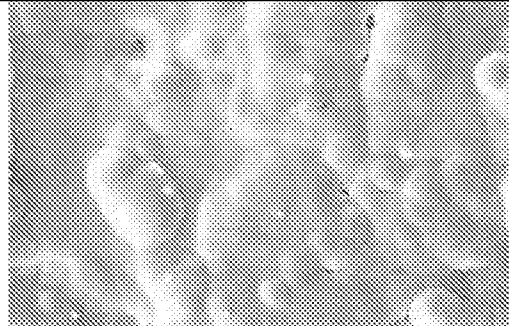
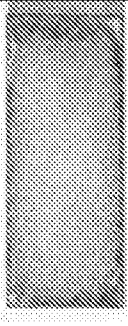
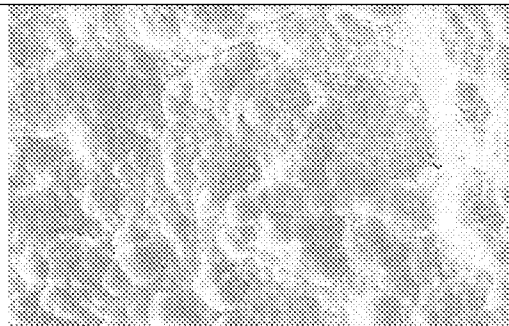
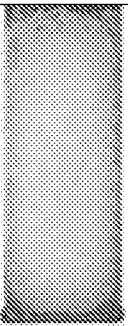
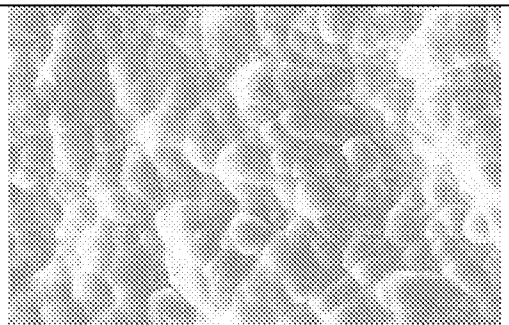
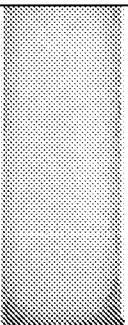
Current Density / Acm^{-2}	Time / mins	SEM 	Photograph
0.3	30		
0.4	30		
0.3 plated for 2 minutes, polarity reversed for 30 s	30		
0.3 plated for 2 minutes, polarity reversed for 12 s	30		

Figure 4

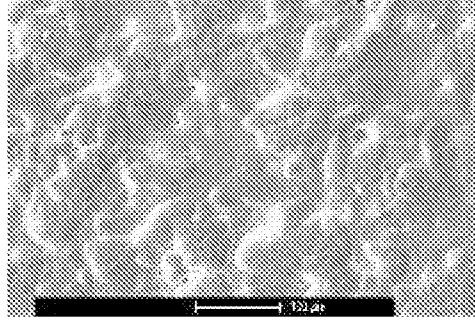
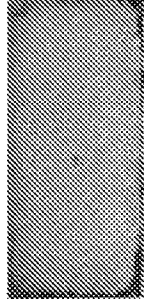
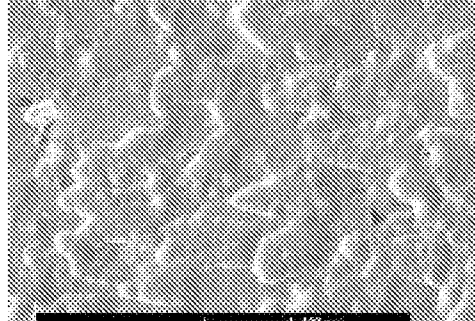
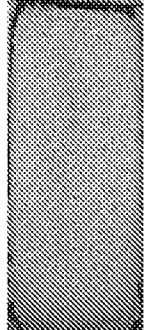
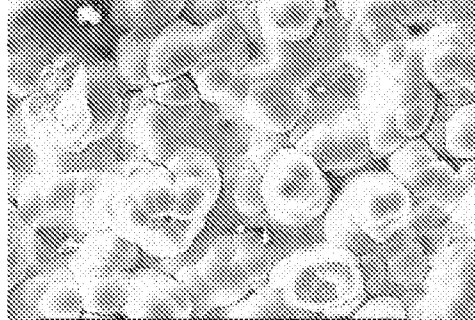
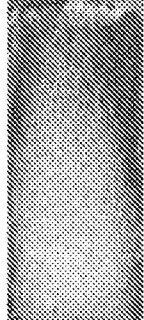

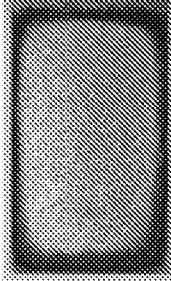
Current Density / Acm^{-2}	Time / mins	SEM	Photograph
0.15	120		
0.2	120		
0.30	120		

Figure 5

Current Density / Acm^{-2}	Time / mins	SEM	Photograph
0.2	30		
0.3	30	