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# 金屬腐蝕電化性質電腦分析系統

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# Digitalized Measurement to Metal Corrosion

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## 摘　要

本研究特別設計一套PC電腦系統分析金屬腐蝕電化性質，快速而精確測定腐蝕之速率，反應參數，及繪製腐蝕極化圖形，並將結果數據圖表列印或存檔備查分析。此系統可做金屬腐蝕抑制劑研發之一有效工具。

## ABSTRACT

A PC computerized electorchemical system for determination of the corrosion rate of a metal is presented. It manages relative potential scans versus the free potential and the digital procedure ensures high reproducibility in imposed signals. Using the system with the Lotus program to perform the experiment and calculate the corrosion rate is available In addition, the program can be used for calculation of the polarization resistance and other corrosion electrochemical parameters. Owing to the superior software, electrochemical corrosion studies can be done faster and easier; Plotting referred time data processing and calculations are totally automated. This study indicates that electrochemical comparative measurements can be performed. Therefore, it is a quite powerful system for selection of the most efficient inhibitor or the best alloy composition.

*key words:* Corrosion, Polarization, Passivity, Pitting, Inhibitor

## 一、前　　言

材料腐蝕對經濟上的損失，資源的浪費，及人體健康生命安全的危害是相當嚴重。由於材料的腐蝕，物件損壞造成經濟上直接的損失，間接地會引起停工，產品，效率之損失。若材料之腐蝕性質不確定，則就必須過度設計，形成材料的浪費，材料腐蝕也可能污染，使人體健康受到威脅，交通運輸之零組件突然腐蝕破坏，更能危及大衆生命，所以在開發及選用材料時，其腐蝕性質之研究有其必要性，其中量測腐蝕速率更是不可或缺的。腐蝕速率測定方法，通常可分兩種，一爲重量損失法，另一種爲電化學法。重量損失法，一般需較長時間，尤其是低腐蝕速率更是費時費事，若腐蝕速率隨時間跟著變化則重量損失法就很難得到滿意的結果。電化學法不僅快速，

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簡易地測定金屬腐蝕率而且可分析出腐蝕反應機構。然而傳統的電化學法係藉記錄紙上之極化曲線（POLARIZATION CURVE）做圖計算得腐蝕速率相當不便，也較不易得到精確之數據。所以本研究特別以電化法設計電腦化系統來測定金屬腐蝕速率及其他腐蝕性質。

## 二、系統內容

硬體主要項目有：

1. 恆定電位儀
2. 精密電表
3. IEEE488界面
4. A/D界面
5. 測試槽
6. PC電腦
7. 記錄器
8. 印表機

硬體配置圖如（圖1）所示，

軟體分三部份：

1. IEEE488界面驅動程式
2. A/D界面驅動程式
3. 腐蝕特性分析程式

軟體提供恆定電位儀控制，訊號收集，訊號處理，數值分析，繪製圖表，列印資料，存檔備查，如（圖 2 ）所示。

軟體主要功能有：

1. 腐蝕電位及電流測定
2. 鈍態電位及電流測定
3. 孔蝕電位及電流測定
4. 過鈍態電位及電流測定
5. 腐蝕電化反應參數測定：TAFEL斜率，Ba及Bc；極化電阻Rp；交換電流Io；TAFEL常數，a及b
6. i-V CURVE圖
7. log（i）-V圖
8. dlog（i）/dV圖
9. $d^2\log(i)/dV^2$圖

## 三、理　論

1. 伽凡尼腐蝕系統（GALVANIC CORROSION SYSTEM）之數值模式及其解[1]：

$$Q=-A\frac{\partial\phi}{\partial x}\Delta t \quad\cdots\cdots(1)$$

$$\Delta\phi=\frac{\partial\phi}{\phi x}(\tfrac{1}{2}\Delta x) \quad\cdots\cdots(2)$$

$$\phi_l=\phi-\tfrac{1}{2}\frac{\partial\phi}{\partial x}\Delta x \quad\cdots\cdots(3a)$$

$$\phi r=\phi+\tfrac{1}{2}\frac{\partial\phi}{\partial x}\Delta x \quad\cdots\cdots(3b)$$

$$\phi_l=\sigma A\frac{\partial}{\partial x}(\phi_l)\Delta t=-\sigma\Delta y\Delta z\frac{\partial}{\partial x}(\phi-\tfrac{1}{2}\frac{\partial\phi}{\partial x}\Delta x)\Delta t \quad\cdots\cdots(4)$$

$$Qr=-\sigma\Delta y\Delta z\frac{\partial}{\partial x}(\phi+\tfrac{1}{2}\frac{\partial\phi}{\partial x}\Delta x)\Delta t \quad\cdots\cdots(5)$$

$$Q=Q_l-Qr=\sigma\Delta y\Delta z\frac{\partial^2\phi}{\partial x^2}\Delta x\Delta t \quad\cdots\cdots(6)$$

$$Q=\sigma\left(\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}\right)\Delta x\Delta y\Delta z\Delta t \cdots(7)$$

$$\Delta\phi=\frac{Q}{\rho C\Delta x\Delta y\Delta z} \quad\cdots\cdots(8)$$

$$Q=\rho C\Delta x\Delta y\Delta z\Delta\phi \quad\cdots\cdots(9)$$

$$\sigma\left(\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}\right)\Delta t=\rho C\Delta\phi \quad\cdots\cdots(10)$$

$$\Delta t\to 0\ \frac{\sigma}{\rho C}\left(\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}\right)=\frac{\partial\phi}{\partial t} \quad\cdots\cdots(11)$$

$$\frac{\sigma}{\rho C}\nabla^2\phi=\frac{\partial\phi}{\partial t} \quad\cdots\cdots(12)$$

$$\nabla^2\phi+\frac{q}{\sigma}=\frac{\rho C}{\sigma}\ \frac{\partial\phi}{\partial t} \quad\cdots\cdots(13)$$

$$\frac{\partial\phi}{\partial t}=0\text{及}q=0\quad\text{則}\begin{cases}\nabla^2\phi=0 & \cdots\cdots(14)\\ i=i(\phi) & \cdots\cdots(15)\end{cases}$$

Kasper[2] 提出4種邊界問題（Boundary conditions）：

1. Dirichlet Boundary Conditions：非極化金屬之極化，如鋅
2. Neuman Boundary Conditions：如陰極保護系統（Cathodic Protection System）
3. Nonlimear Boundary Conditions：如一般

極化 ( Electrode Polarization )

4. Mixed Boundary Condary Conditins：以上三種之任何一混合情況

本研究是以第 3 邊界問題爲主，也就是一般金屬之極化，屬於非線性極化問題。

2. 混合電位理論 ( Mixed Potential Theory )：

在只有活性極化控制之腐蝕非線性邊界問題，可由Buter-Volmer Equation方程式[3]得解：

$$i_{net}=i_o\left[\exp\frac{-\beta F\varepsilon}{RT}-\exp\frac{(1-\beta)F\varepsilon}{RT}\right] \cdots\cdots (16)$$

或由 Tafel Equation 表示之：

$$\varepsilon_a=\frac{RT}{\alpha zF}\ln i_o-\frac{RT}{\alpha zF}\ln i_a \cdots\cdots (17)$$

金屬之極化可由以下三式描述之：

$$i_m=i_{om}10^{\varepsilon_m/\beta_m} \cdots\cdots (18)$$

$$\varepsilon_m=\beta_m\log\left(\frac{i_m}{i_{om}}\right) \cdots\cdots (19)$$

$$i_r=i_{or}10^{\varepsilon_r/\beta_r} \cdots\cdots (20)$$

若腐蝕速率受活化及濃度極化控制，則可由下列式表示之：

$$\varepsilon_m=\beta_m\log\left(\frac{i_m}{i_{om}}\right)+2.3\frac{RT}{ZF}\log\left(1-\frac{im}{ipass}\right) \cdots\cdots (21)$$

$$i_m=\frac{i_{om}10\varepsilon_m/\beta_m}{\left[1+\left(\frac{i_{om}10(\varepsilon_m/\beta_m)}{i_{pass}}\right)^{km}\right]^{1/km}} \cdots\cdots (22)$$

$$\varepsilon_r=\beta_r\log\left(\frac{i_r}{io_r}\right)+2.3\frac{RT}{ZF}\log\left(1-\frac{i_r}{i_l}\right) \cdots\cdots (23)$$

$$i_r=\frac{i_{or}10\varepsilon_r/\beta_r}{\left[1+\left(\frac{i_{or}10(\varepsilon_r/\beta_r)}{i_l}\right)^{kr}\right]^{1/kr}} \cdots\cdots (24)$$

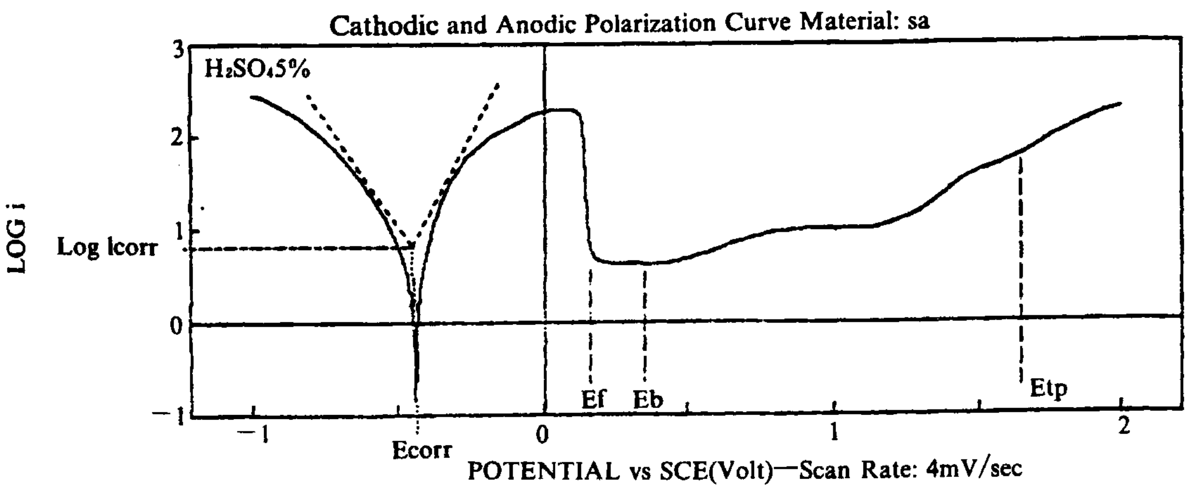
3. 腐蝕速率作圖法(Graphical Expressing)：

根據E-logi之圖決定腐蝕電流[4]，其說明如下圖所示。

4. 腐 蝕 速 率 Tafel 外 插 法 (Tafel Extrapotation)：

依據混合電位理論，Wagner and Trand 提出 Tafel 外插法測定腐蝕速率[5]，其原理由下列式子說明之。

$$i_a=i_{oa}\left\{\exp\left[\frac{Z_a(1-\beta_a)\varepsilon_a}{RT}\right]-\exp\left[\frac{-Z_aF\beta_a\varepsilon_a}{RT}\right]\right\} \cdots\cdots (25)$$



$$i_{net} = i_a - i_c \quad \cdots\cdots (27)$$

當ε>>0則上列二式爲：

$$i_a = i_{oa}\exp[\frac{(1-\beta_a)Z_aF\varepsilon_a}{RT}] \quad \cdots\cdots (28)$$

$$i_c = i_{oc}\exp[\frac{(-\beta_cZ_cF\varepsilon_c)}{RT}] \quad \cdots\cdots (29)$$

$$\log\frac{i_a}{i_{oa}} = \frac{F(1-\beta_a)Z_a\varepsilon_a}{RT} \quad \cdots\cdots (30)$$

$$\frac{\partial\varepsilon_a}{\partial \log i_a} = \frac{RT}{Z_aF(1-\beta_a)} \quad \cdots\cdots (31)$$

$$i_{corr} = i_{oa}\exp[\frac{(1-\beta_a)Z_aF\varepsilon_{corr}}{RT}] \quad \cdots\cdots (32)$$

$$i_{corr} = ioa\ \exp[\frac{-\beta_cZ_cF\varepsilon_{corr})}{RT}] \quad \cdots\cdots (33)$$

$$\log i_a = a_a + b_a\varepsilon_a \quad \cdots\cdots (34)$$

$$\log i_c = a_c + b_c\varepsilon_c \quad \cdots\cdots (35)$$

$$a_c = \log i_{oc} \quad \cdots\cdots (36)$$

$$a_a = \log i_{oc} \quad \cdots\cdots (37)$$

$$b_a = \frac{Z_a(1-\beta_a)F}{RT} = \frac{\partial \log i_a}{\partial\varepsilon} \quad \cdots\cdots (38)$$

$$b_c = \frac{-Z_c\beta_cF}{RT} = \frac{\partial \log i_c}{\partial\varepsilon} \quad \cdots\cdots (39)$$

則

$$\boxed{i_{corr} = \exp[a_a + b_a\varepsilon_{corr}]} \quad \cdots\cdots (40)$$

$$\boxed{i_{corr} = \exp[a_c + b_c\varepsilon_{corr}]} \quad \cdots\cdots (41)$$

5. 腐蝕速率直線極化法 ( Linear Polarization )[6]

在活性控制系統之極化曲線在接近腐蝕電位區域是直線關係，可用下列式子表之。

$$i_a = i_{corr}\exp[(1-\beta_a)\frac{Z_aF}{RT}\varepsilon] = i_{corr}\exp[\frac{2.3\varepsilon}{\beta_a}] \quad \cdots\cdots (42)$$

$$[\frac{\partial\varepsilon}{\partial \log i_a}]_{\varepsilon\to 0} = \frac{2.3RT}{(1-\beta_a)Z_aF} = B_a \quad \cdots\cdots (44)$$

$$[\frac{\partial\varepsilon}{\partial \log i_c}]_{\varepsilon\to 0} = \frac{2.3RT}{\beta_cZ_aF} = B_c \quad \cdots\cdots (45)$$

由上式子可得

$$\boxed{i_{corr} = \frac{B_aB_c}{(B_a+B_c)}[\frac{i_{app}}{\varepsilon}]} \quad \cdots\cdots (46)$$

若要得到理想數值ε必須接近約30mV

6. 腐蝕極化電阻法(Polarization Resistance)[7]

極化電阻法是由 Stern and Geary 所提出，腐蝕系統之 Ba 及 Bc 平均值爲0.12V，則

$$icorr = [\frac{BaBc}{2.3(Ba+Bc)}][\frac{iapp}{\varepsilon}]$$

$$= [\frac{0.12\times0.12}{2.3(0.12+0.12)}][\frac{1}{Rp}] = \frac{0.026}{Rp} \quad \cdots\cdots (47)$$

所以腐蝕電流可以下式表示之

$$\boxed{icorr = \frac{0.026}{Rp}} \quad \cdots\cdots (48)$$

這裡 $Rp = [\frac{\partial\varepsilon}{\partial i}]_{i=0} = \frac{BaBc}{(Ba+Bc)io}$

Bonhoeffer and Jena[8] 定義 $R_p$ 爲極化電阻 ( Polarization Resistance )

## 符號說明

A =Tafel constant; area

B =Tafel constant

iapp =Applied current

icorr = Corrosion current
l = Left
Pass = Passive
R = Gas constant
r = Right
T = Absolute temperature
x = One linear dimension
σ = Electrical conductivity
β = Transfer coefficient
a = Anode
c = Cathode
io = Exchange current
K = Constant
M = Metal
Q = Charge transferred
R = Polarization resistance
r = Reduction
t = Time
z = No. of electrons transferred
ϕ = Electric potential
ε = Overpotential

## 四、實驗過程

**1. 硬體製作：**

本系統之硬體裝置如圖 1 所示，其中電腦是 IBM 相容個人電腦，恆定電位儀是法國 TACUSSEL 公司產品 Pulse Polarographic System PRG5 極譜儀。IEEE488界面卡是國內研華科技公司製造產品 PCL848 界面卡。參考極為飽和甘汞電極SCE，輔助電極為白金電極。

**2. 軟體製作：**

本研究應用上述硬體裝置及界面自行設計開發一系統以 LOTUS 1-2-3 巨集程式撰寫，其內容包括極化量測之控制及訊號數據之傳輸，極化分析，腐蝕參數計算及極化圖之顯示、列印、存檔等功能。其測試結果和圖表之顯示及列印如圖 2 所示，其中包含有各種電化參數外並分析出腐蝕之一些性質如腐蝕電位 Ec，鈍態電位 $E_r$，過鈍態電位 $E_{tp}$，孔蝕電位 Epit 以及相對應之電流密度 Ic, If, Itp, Ipit，而腐蝕電流又以極化電阻法，直線極化法和 Tafel 外插法分析所得結果分別為 R. Ic, L. Ic 和 T. Ic。有關量測系統之程式內容如附錄 1 所示，腐蝕極化分析程式內容如附錄 2 所示。

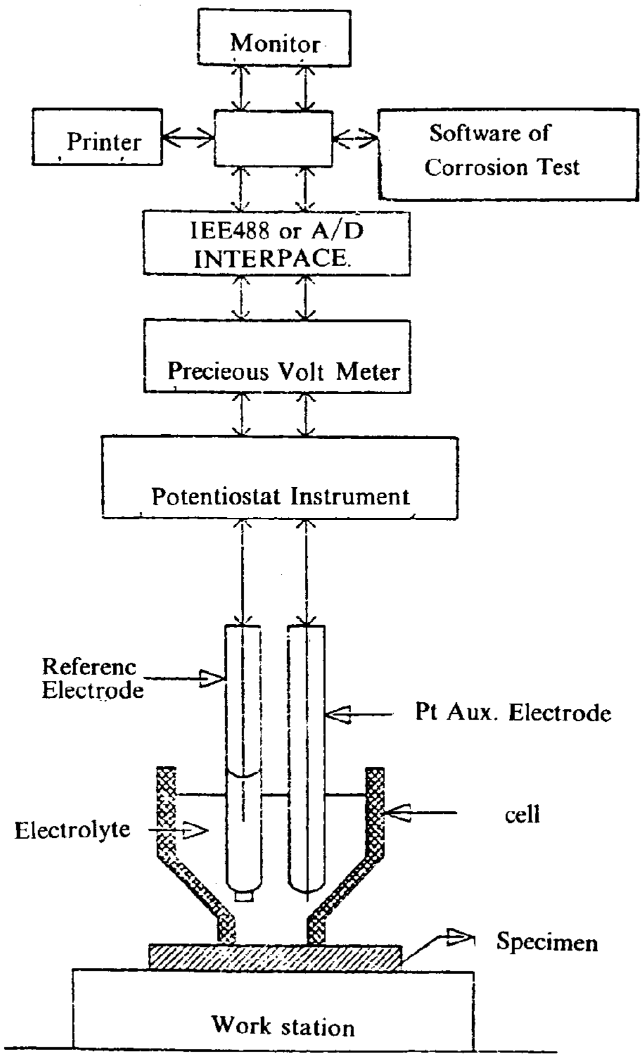



圖 1　極化曲線量測之硬體配置圖

**3. 實驗步驟：**

為了測試本系統之軟硬體功能，本研究準備一些金屬試片如 Cu, Fe, Ni, Pb, Zu, Sn, Pt，

304 不銹鋼，430不銹鋼、黃銅，無電鍍鎳一磷非晶質鍍層，鎳一氧化鋁複合鍍層及 Cu-P-Sn-Ni 合金，試片表面研磨至400號砂紙，用蒸餾水及丙酮清洗乾燥之，然後放置試槽底下以絕緣橡膠墊圈形成一半徑1mm之測試面積，再注入配製好的測試電解液如 KCl, NaCl, HCl, $HNO_3$, $H_2SO_4$ 之水溶液及 DMSO 非水溶液以4mV/sec掃描速率從－1V至＋2V（相對SCE）做電解極化測試，測試中之電壓一電流經 IEEE488 界面傳輸至 PC 電腦，經由本系統軟體分析計算腐蝕電化性質及繪製極化曲線圖顯示於監視器上或列印，儲存於記憶體中建立一極化曲線資料庫供整體分析所用。本研究爲了比較此系統與重量損失法所測之腐蝕電流密度，做一系列 Cr 及 Mo 合金元素及應力消除熱處理對鑄件之腐蝕行爲之影響測試，這些鑄件化學成份組成如表1所示。

表 1　試片之化學成份（wt%）

Table 1　Chemical compositions of samples（wt%）

| Sample | C | Si | Mn | Mo | Cr | Fe |
|---|---|---|---|---|---|---|
| A | 0.08 | 0.36 | 1.12 | 0.00 | 0.002 | 98.437 |
| B | 0.08 | 0.34 | 1.17 | 0.00 | 1.27 | 97.139 |
| C | 0.08 | 0.36 | 1.4 | 0.00 | 3.85 | 94.309 |

## 五、結果與討論

由本實驗過程及本系統分析所得數據與極化曲線圖得知下列結果：

1. 在電解極化過程，若有濃度極化現象，多種反應，或其他外來之效應，極化曲線會被扭曲而不能到 Tafel 直線部份，則 Tafel 外挿法就不能得到滿意之腐蝕電流，如圖 3 中所示 T. Ic和 R. Ic 及 L. Ic 相差甚多。
2. 極化電阻法得之腐蝕電流 R. Ic 與直線極化法得之腐蝕電流 L. Ic 和 Tafel 外挿法所得之腐蝕電流 T. Ic 其值不相差超過 3 倍。如圖 4 所示。
3. 表 2 所示由本系統所測得之腐蝕電流 R. Ic. T. Ic 及 L. Ic 以4mV/sec 掃描速率所得之結果與重量損失法所得之結果相當符合，若掃描速率太慢因反應物，生成物之溶液環境及測試金屬表面狀態都已有所改變，若太快則平衡不易達成而無法得到一定滿意之結果。

表 2　重量損失和腐蝕電流密度

Table 2　Weight loss and corrosion current density

| Sample | aA | aB | aD | sA | sB | sD |
|---|---|---|---|---|---|---|
| dwt-1hr | 12.5 | 17.4 | 11.7 | 14.4 | 13.38 | 14.220 |
| dwt-3hr | 36.4 | 60.9 | 39.2 | 52.8 | 46.47 | 51.070 |
| dwt-5hr | 59.4 | 101. | 71.6 | 91.1 | 75.63 | 84.250 |
| dwt/Avg | 12.2 | 19.3 | 13.0 | 16.7 | 14.66 | 16.031 |
| dwt/3hr | 12.1 | 20.3 | 13.0 | 17.6 | 15.49 | 17.023 |
| dwt/5hr | 11.8 | 20.2 | 14.3 | 18.2 | 15.12 | 16.850 |
| Ic×10 | 3.76 | 12.7 | 6.82 | 7.26 | 4.196 | 5.6425 |
| ipy×100 | 0.05 | 0.84 | 0.57 | 0.73 | 0.644 | 0.7040 |
| mpy | 5.36 | 8.49 | 5.73 | 7.36 | 6.441 | 7.0409 |
| mdd | 292. | 463. | 313. | 402. | 352 | 0.7695 |
| Icorr | 0.58 | 0.92 | 0.62 | 0.80 | 0.704 | 0.7695 |
| Ic | 0.37 | 1.27 | 0.68 | 0.72 | 0.419 | 0.5642 |

where
dwt-1hr is weight loss after 1 hr immersion, mg
dwt-3hr is weight loss after 3 hr immersion, mg
dwt-5hr is weight loss after 5 hr immersion, mg
dwt/1hr is average weight loss per hr, mg/hr
dwt/3hr is weight loss per hr after 3 hr immersion, mg/hr
dwt/5hr is weight loss per hr after 5 hr immersion, mg/hr
ipy is corrosion rate, in/year
mpy is corrosion rate, miles per year
mdd is corrosion rate, mg per square dm per day
Icorr is corrosion current, $mA/cm^2$, by weight-loss method
Ic is corrosion current, $mA/cm^2$, by polarization method

4. 腐蝕行爲相當複雜，實驗之重覆性不易完全重現，其原因是由於金屬表面狀態改變，組成不均勻性，結構不同，不純物、偏析、加工、熱處理、氧化物膜、傷痕、異種金屬接觸、電解液之濃度、溫度差、溶解氣體、液體之流動，液體與金屬接觸狀態……等等都

會影響極化曲線，如圖5所示不同合金元素成份及熱處理之影響。所以要得到良好的重覆性必須很小心及仔細地做極化曲線測試。

表3 實驗數據中之腐蝕參數
Table 3 Corrosion parameters in tested data

| Sample | aA | aB | aD | sA | sB | sD |
|---|---|---|---|---|---|---|
| Etp | 1.513 | 1.572 | 1.524 | 1.513 | 1.604 | 1.580 |
| Ec | -0.395 | -0.433 | -0.395 | -0.435 | -0.414 | -0.443 |
| Ef | 0.062 | 0.220 | 0.244 | 0.354 | 0.437 | 0.461 |
| Epit | 0.020 | 0.108 | 1.376 | 0.145 | 0.346 | 0.351 |
| Efb | 0.062 | 0.220 | 0.244 | 0.351 | 0.473 | 0.459 |
| dEp | 1.450 | 1.351 | 1.279 | 1.159 | 1.167 | 1.119 |
| Itp | 67.87 | 19.83 | 19.30 | 43.19 | 14.46 | 4.307 |
| Ic | 0.376 | 1.278 | 0.683 | 0.727 | 0.420 | 0.564 |
| If | 8.580 | 5.752 | 11.06 | 4.055 | 4.052 | 4.759 |
| Ipit | 82.66 | 71.10 | 191.9 | 22.29 | 56.77 | 55.84 |
| Ifb | 8.580 | 5.752 | 11.06 | 4.055 | 4.052 | 4.759 |
| Ip | 38.22 | 12.79 | 15.18 | 23.62 | 9.26 | 4.53 |
| Rp | 68.08 | 20.03 | 37.51 | 35.22 | 61.01 | 45.37 |
| ba | 0.137 | 0.132 | 0.147 | 0.130 | 0.215 | 0.218 |
| bc | 0.129 | 0.107 | 0.122 | 0.110 | 0.121 | 0.116 |
| Vi | -1.000 | -1.000 | -1.000 | -1.000 | -1.000 | -1.000 |
| Vf | 2.000 | 2.000 | 2.000 | 2.000 | 2.000 | 2.000 |
| Io | 0.008 | 2.265 | 0.049 | 0.148 | 0.061 | 0.031 |

Where
a is as-welded
s is stress-relieved
Etp is Transpassivation Potential, Volt vs SCE
Ec is Corrosion Potential, Volt vs SCE
Ef is Flade Potential, Volt vs SCE
Epit is Pitting Potential, Volt vs SCE
Efb is Flatband Potential, Volt vs SCE
Itp is Transpassive Current Density, $mA/cm^2$
If is Flade Current Density, $mA/cm^2$
Ipit is Pitting Current Density, $mA/cm^2$
Ifb is Flatband Current Density, $mA/cm^2$
Ip is Passivation Current Density, $mA/cm^2$
Rp is Polarization Resistance, ohm $cm^2$
ba is Anodic Tafel Constant, V/decade
bc is Cathodic Tafel Constant, V/decade
Vi is Initial Scan Potential, Volt vs SCE
Vf is Final Scan Potential, Volt vs SCE
Io is Exchange Current Density, $mA/cm^2$

## 六、結　論

1. 經由本電腦化腐蝕測試系統可快速準確測出腐蝕電流及腐蝕電位。
2. 金屬和合金在鈍態環境中，本系統可測出鈍態電位（Passivating potential），鈍態電流（Passivating current），過鈍態電位（Trans-passive potential）及過鈍態電流（Trans-passive current）。
3. 本系統同時顯示三種方法計算出之腐蝕電流及其他電化動力參數可做腐蝕性質、電化反應之研究，而一般商業軟體沒有此功能。
4. 本系統可做爲開發腐蝕抑制劑之一有效工具。

## 七、誌　謝

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| | | | | | |
|---|---|---|---|---|---|
| FILE:so4ad2 | 1.513 | =Etp　Itp= | 32.588 | Rp= | 37.5 |
| Scan Rate: 4 mV/sec | -0.395 | =Ec　Ic= | 0.683 | Ba= | 0.147 |
| Electrode: SCE/Pt | 0.244 | =Ef　If= | 11.057 | Bc= | 0.122 |
| Material:ad | 1.021 | =Epit　Ipit= | 19.286 | Inital Volt | -1.000 |
| T=21 C | 0.244 | =Efb　Ifb= | 11.057 | Final Volt | 2.000 |
| H2SO4 5% | 1.269 | =dEp　Ip= | 21.823 | Io= | 0.049 |

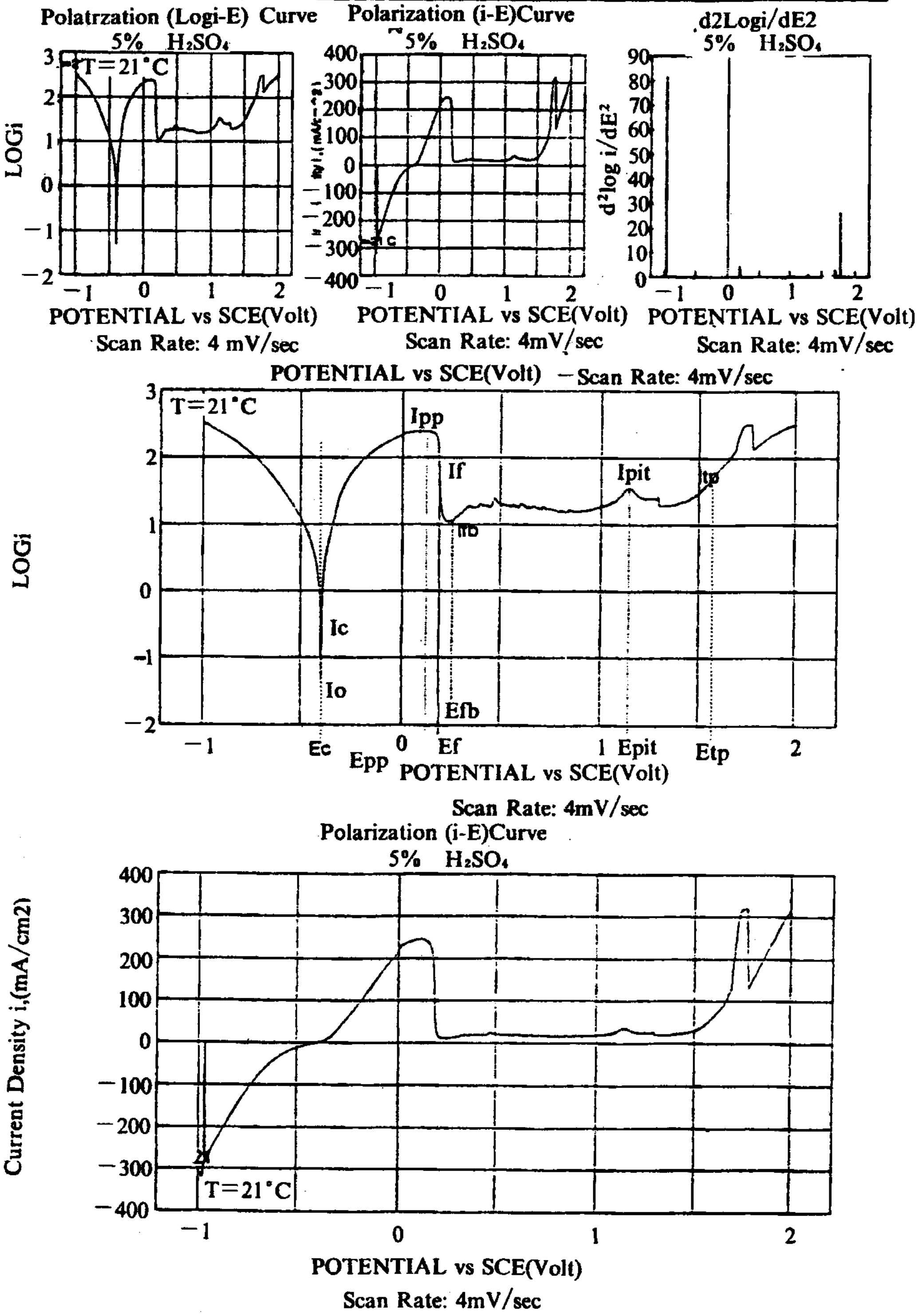


圖 2　極化曲線圖及測試結果列印之案例 1

| | | | | | | |
|---|---|---|---|---|---|---|
| File Name: 2005002 | 0.347509 | =a | Rp= | 0.2243492 | Ifb= | -0.04047 |
| Scan Rate: 2 mV/sec | -1.65800 | =b | i0 = | 0.005311 | Itp= | 0.962997 |
| Work Electrode:CuNiSnP | -0.5287 | =Ep | Ec= | -0.36963 | Ip= | -4.1573 |
| Ref/Aux Electrode:SCE/Pt | -0.1916 | =Etp | Efb= | -0.38219 | Initial Potential | -1 |
| Condition:pH=6.9 T=25C | 0.056312 | =Bc | Ba= | 2.3845297 | Final Potential | 1 |
| 0.3% NaCl/H2O | 0.10647 | =L.Ic | T.Ic= | 2.225919 | R.Ic= | 0.115890 |

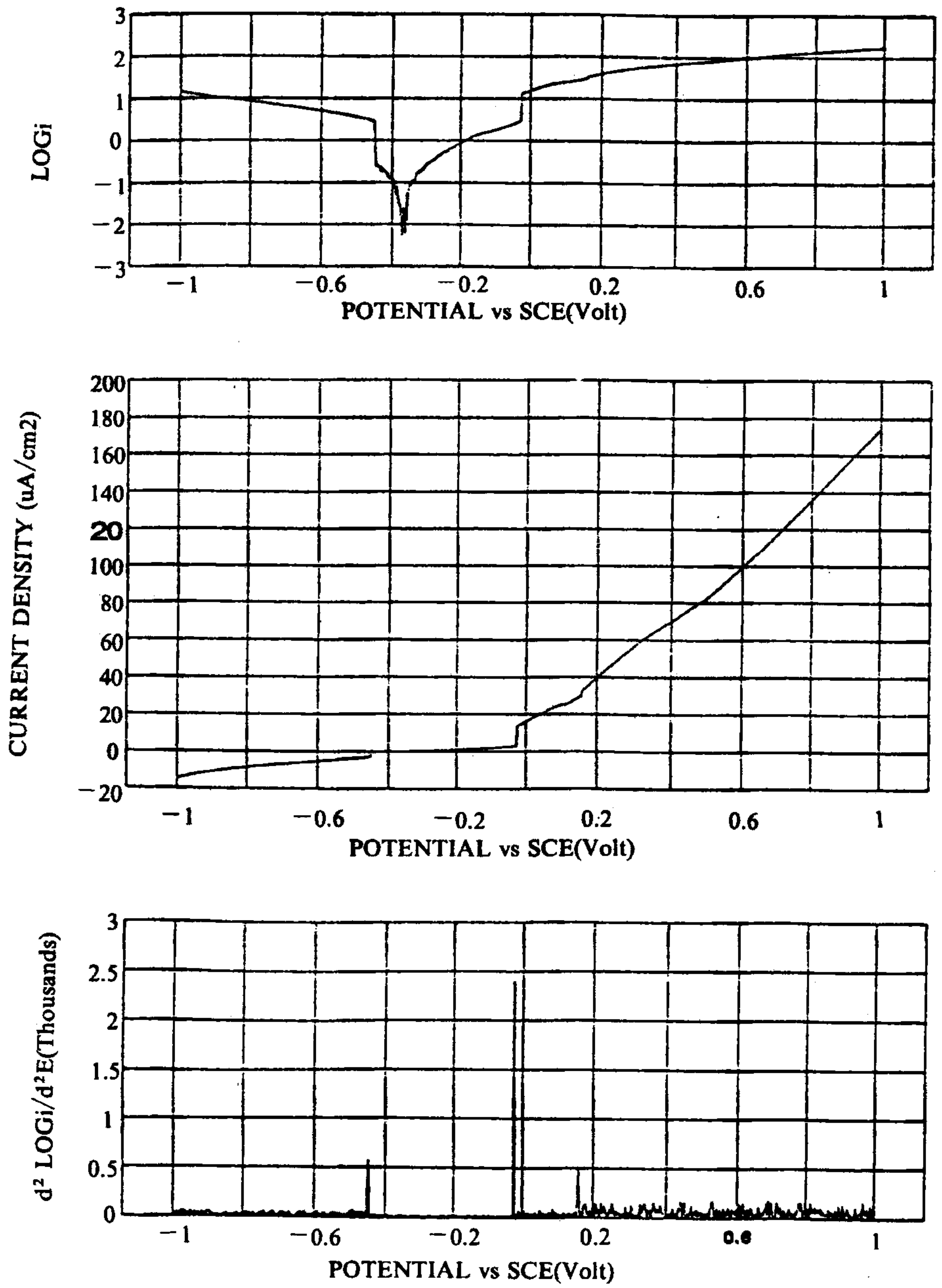


圖 3 極化曲線圖及測試結果列印之實例 2

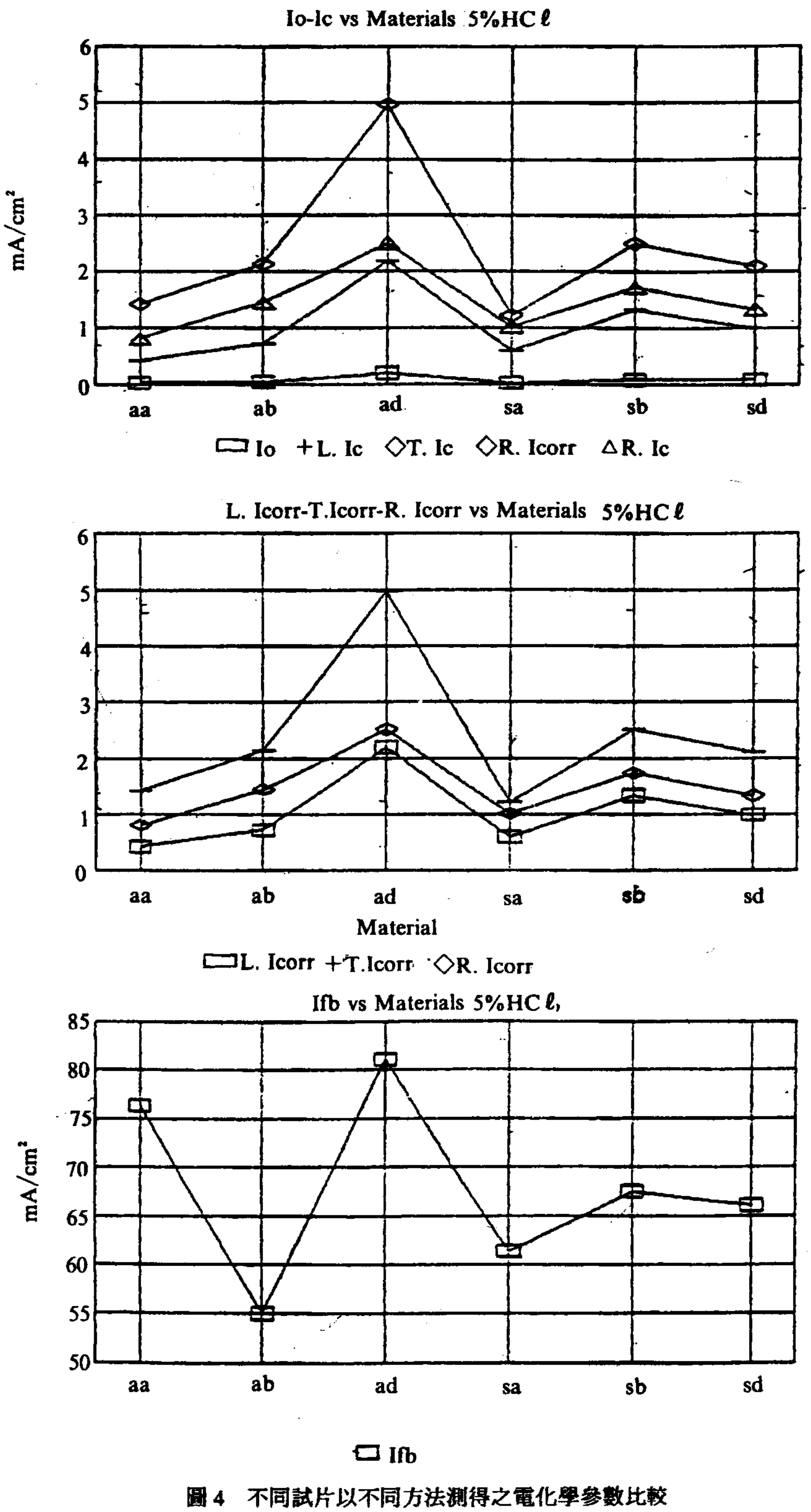


圖4　不同試片以不同方法測得之電化學參數比較

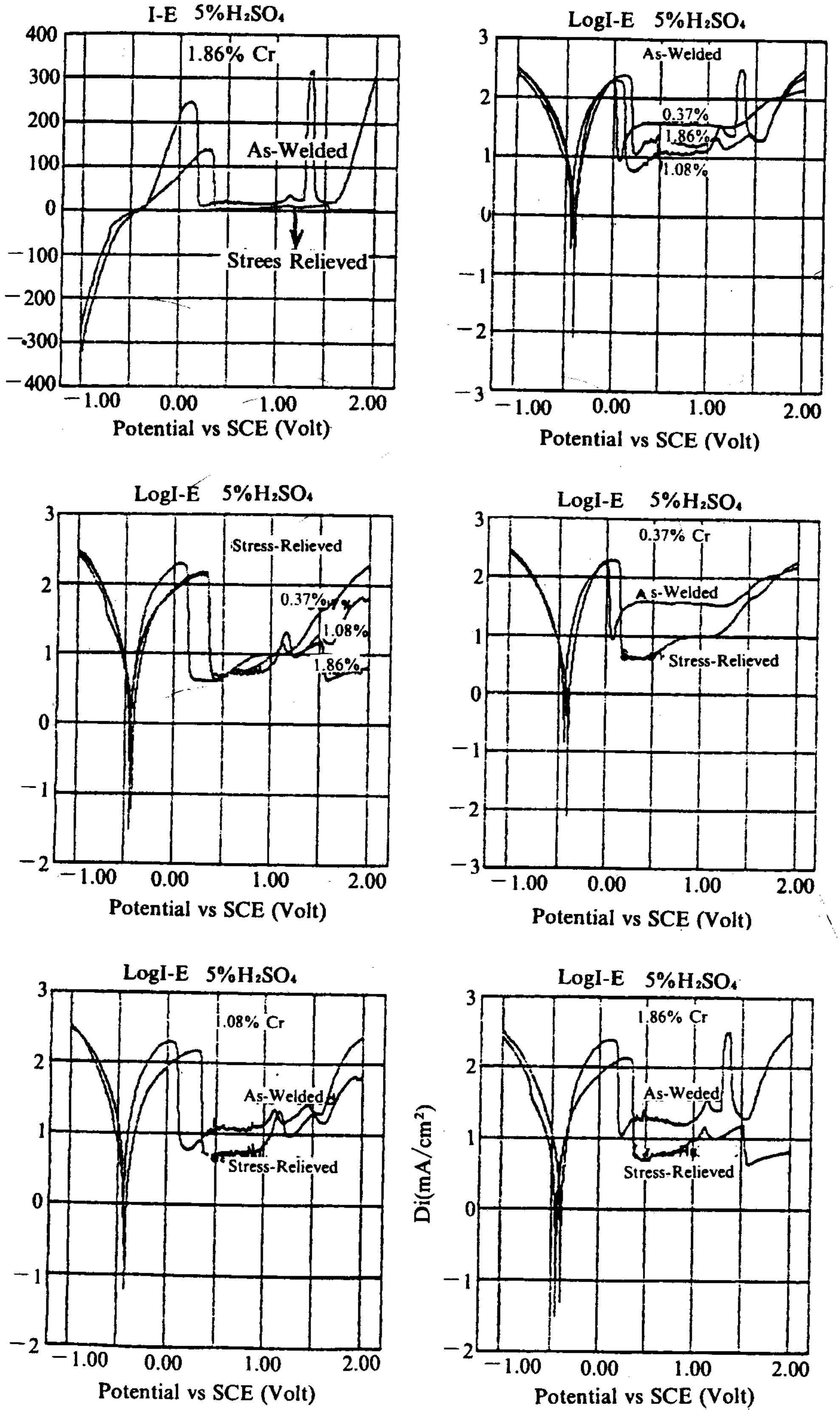


圖 5 不同狀態下之試片在 5%$H_2SO_4$溶液之極化曲線

## 附錄1. 極化曲線圖量測 LOTUS 程式

```
Polarization Measurement
{Ieeeinit}
{WRITELN "OUTPUT 26;M2X"}
{WRITELN "HELLO"}
{READLN Hello}
{CheckSRQ 10}
{WRITELN "STATUS"}
{READLN Status}
{CheckSRQ 20}
{WRITELN "OUTPUT 26;F0R3X"}
{CheckSRQ 30}
{WRITELN ENTER 26}
{READLN Reading}
{CheckSRQ 40}
{LET Voltage,@VALUE(@MID(Reading,4,11))}
{FOR Index,0,439,1,Sum1}
{\O}
{\P}


{OPEN IEEE,W}
{WRITELN RESET}
{WRITELN EOL IN CR}
{WRITELN FILL ERROR}
{RETURN}

{WRITELN ENTER 26}
{READLN Reading}
{CheckSRQ 100}
{PUT Voltages,0,Index,@VALUE(@MID(Reading,4,11))}
{RETURN}

{DEFINE Signal:VALUE}
{WRITELN SPOLL}
{READLN SP}
{LET SP,@VALUE(@MID(SP,0,@LENGTH(SP)-1))}
{IF SP=0}{BLANK ST195}{RETURN}
{WRITELN SPOLL 26}
{READLN ST195}
{LET ST195,@VALUE(@MID(ST195,0,@LENGTH(ST195)-1))} ~
{IF DIO7}{BRANCH 195SRQ}
{BEEP}{GETLABEL "Non-195 SRQ detected! Press Return.",TypeHere}
{RESTART}{RETURN}
{IF DIO6}{BRANCH 195ERR}
{IF DIO5}{BEEP}{GETLABEL "195 Status: BUSY. Press Return.",TypeHere}
{IF DIO4}{BEEP}{GETLABEL "195 Status: READING DONE. Press Return.",TypeHere}
{IF DIO3}{BEEP}{GETLABEL "195 Status: BUFFER 1/2 FULL. Press Return.",TypeHere}
{IF DIO2}{BEEP}{GETLABEL "195 Status: BUFFER FULL. Press Return.",TypeHere}
{IF DIO1}{BEEP}{GETLABEL "195 Status: OVERFLOW. Press Return.",TypeHere}
{RETURN}
{IF DIO5}{BEEP}{GETLABEL "195 Status: FAILED SELFTEST. Press Return.",TypeHere}
{IF DIO4}{BEEP}{GETLABEL "195 Status: TRIGGER OVERRUN. Press Return.",TypeHere}
{IF DIO3}{BEEP}{GETLABEL "195 Status: NO REMOTE. Press Return.",TypeHere}
{IF DIO2}{BEEP}{GETLABEL "195 Status: ILLEGAL COMMAND. Press Return.",TypeHere}
{IF DIO1}{BEEP}{GETLABEL "195 Status: ILLEGAL COMMAND OPTION. Press Return.",TypeHere}
{RETURN}
```

## 附錄2. 極化曲線分析 LOTUS 程式

**ANALYSIS**

**Corrosion Parameters**

```
{app1}x{HOME}{GOTO}b7~/df{esc}.{L}{END}{D}{R}~1~1~8000~~/ml.{end}{d}~
{GOTO}c7~@log(@abs(a7))~/c~.{L}
{END}{D}{R}~
/rv.{END}{D}~~{goto}b4~+{l}{END}{D}{R}~/rv~~{GOTO}F4~
{GOTO}d7~+$ei~{d}~+{u}+($ef-$ei)/$B$4~/c~.{L}{END}{D}{R}~~/rv.{END}{D}~~
{goto}b7~/dsrd.
{END}{D}{R}~pc7~a~g{GOTO}B3~+b7~/rv~~{edit}{home}'~
{GOTO}ec~@IF(a7<0,$ei+@VALUE(b3)*@ABS($Ef-$EI)/@value(b4),
$ei-@VALUE(b3)*@ABS($Ef-$EI)/@VALUE(b4))~/rv~~/ds~~p{l}~~g
/xi(b4>100)~{goto}a2~Scan Rate: 40 mV/sec~
/xi(b4>300)~{goto}a2~Scan Rate: 20 mV/sec~
/xi(b4>400)~{goto}a2~Scan Rate: 10 mV/sec~
/xi(b4>1000)~{goto}a2~Scan Rate: 4 mV/sec~
/xi(b4>2000)~{goto}a2~Scan Rate: 2 mV/sec~
/xi(b4>4000)~{goto}a2~Scan Rate: 1 mV/sec~
{goto}d7~/c.{END}{D}~{R}~+{R}-$EC~/c~.{end}{D}~/rv.{END}{D}~~
{goto}b1~@ABS(@value(b3)-@round(b4*.03/@abs(ef-ei),0))~/rv~~{edit}{home}'~
{GOTO}{\b1}~
/dry{R 4}
.{u 2}~x{R}{R}
.{u 2}~op8~g
{GOTO}bc~@abs(+r15*2)~/rv~~
{goto}b1~@ABS(@value(b3)-@round(b4*.03/@abs(ef-ei),0))~/rv~~{edit}{home}'~
{GOTO}{\b1}~
/dry{R 4}
.{d 2}~x{R}{R}
.{d 2}~op8~g
{GOTO}ba~
@abs(+r15)*2~/rv~~
{GOTO}{\b1}~
/drY{R 4}{u 2}.{d 4}~X
{u 2}.{d 4}~op8~g
{HOME}
{GOTO}rp~
+r15*4~/rv~~
{GOTO}lic~
+ba*bc/rp/(bc+ba)/2.303~/rv~~
{GOTO}io~
10^@min(logi)~/rv~~
{GOTO}ric~
@ABS(0.0256/rp)~{goto}f10~@ABS((+a9-2*a8+a7)/($d$8-$d$7)^2)/1000/1000~/c~.{l}{end}{d}{r}~
/xi(a7<0)~{goto}b1~@ABS(@value(b3)-@round(0.1*b4/@abs(ef-ei),0))~/rv~~{edit}{home}'~
/xi(a7>0)~{goto}b1~@ABS(@value(b3)+@round(0.1*b4/@abs(ef-ei),0))~/rv~~{edit}{home}'~
/xi(a7>0)~{goto}e2~'Bc=~{d}'Ba=~
/xi(a7<0)~{goto}e2~'Ba=~{d}'Bc=~
{home}/rva1.f6~~
{GOTO}f8~/dsrd.{end}{D}{l 5}~pf8~a~g{goto}efb~+e8~/rv~~{goto}ifb~+a8~/rv~~
{GOTO}epp~@if(@ABS(E9-E8)<.2,+e9,+e10)~/rv~~{goto}ipp~@if(@abs(e9-e8)<.2,+a9,+a10)~/rv~~
{GOTO}ep~@if(@ABS(E10-E11)>.2,+e10,+e11)~/rv~~{goto}ip~@if(@abs(e10-e9)>.2,+a10,+a11)~/rv~~
/xi(a7>0)~/dspe8~d~g
/xi(a7<0)~/dspe8~a~g
{home}
/dsrda330.f942~pa8~a~g
{GOTO}ep~+e330~{goto}ip~+a330~
/dsrda8.f942~pb8~a~g
/dsrda330.f942~pf8~a~g
{GOTO}Epp~+e330~{goto}Ipp~+a330~
/dsrda8.f942~pb8~a~g
/dsrda330.f942~pa8~a~se8~a~g
{GOTO}Efb~+e330~{goto}Ifb~+a330~
/dsrda945.f1127~pa8~a~g
{GOTO}Etp~+e946~{goto}Itp~+a946~
/dsrda945.f1127~pb8~a~g
```