

咪唑啉类化合物在 HCl 溶液中对 碳钢的缓蚀机理分析

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摘要: **目的** 研究咪唑啉 (IM) 及咪唑啉基脲 (IU) 在盐酸溶液中对碳钢的缓蚀性能。**方法** 采用静态失重法、电化学测试技术、表面形貌及官能团分析、热力学等温方程等方法, 研究缓蚀剂在不同温度的盐酸溶液中对 Q235 碳钢的缓蚀性能和吸附规律。**结果** 在静态失重试验中, 室温下, 随着 IM、IU 缓蚀剂的加入, 碳钢的腐蚀速率从 $12.54 \text{ mg}/(\text{cm}^2 \cdot \text{h})$ 分别降低到 5.132 、 $0.145 \text{ mg}/(\text{cm}^2 \cdot \text{h})$, IM、IU 的缓蚀率分别为 59.1% 和 98.9% 。随着温度的升高, 缓蚀效率略有下降。极化曲线试验表明, 增加两种缓蚀剂的浓度, 腐蚀电位负移, 阳极电流密度下降明显。交流阻抗的测试显示, 随着两种缓蚀剂浓度的增大, 拟合参数 R_{ct} 增大、 C_{dl} 减小, 证明缓蚀剂在金属表面取代了水, 并吸附成膜。研究等温吸附模型发现, 两种缓蚀剂分子在碳钢表面的吸附符合 Langmuir 等温吸附方程, 且根据 SEM 及 XPS 分析, 证明缓蚀剂分子通过 N 原子与金属形成共价键, 在金属表面吸附成膜。**结论** 咪唑啉和咪唑啉基脲对碳钢均具有缓蚀效果, 且咪唑啉基脲的缓蚀效果更优异。两种缓蚀剂均属于混合型缓蚀剂, 且以抑制阴极腐蚀反应速率为主。两种咪唑啉化合物在碳钢表面的吸附过程为自发放热过程, 其吸附规律遵循 Langmuir 吸附等温模型, 属于单分子层吸附。

关键词: 咪唑啉基脲; 缓蚀剂; 盐酸腐蚀; 碳钢; 电化学; 吸附

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Corrosion Inhibition Mechanism of Imidazoline Compounds for Carbon Steel in HCl Aqueous Solution

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ABSTRACT: The work aims to investigate the corrosion inhibition of imidazoline (IM) and imidazolidinyl urea (IU) for carbon steel in HCl solution. Weight loss method, electrochemical technique, surface analysis, functional group analysis and thermody-

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namic isothermal equation were used to study corrosion property and adsorption rule of corrosion inhibitors for Q235 carbon steel HCl solution at different temperature. In the weight loss test, as the corrosion inhibitor (IM, IU) was added at ambient temperature, the corrosion rate decreased from 12.54 mg/(cm²·h) to 5.132 and 0.145 mg/(cm²·h) respectively and the corrosion inhibition rate of corrosion inhibitors was 59.1% and 98.9% respectively. Furthermore, the corrosion inhibition efficiency decreased with the increase of temperature. From polarization curve test, the corrosion potential of two corrosion inhibitors was moving forward and the cathode current density decreased obviously as concentration increased. From the alternating current resistance test, with the increase of concentration, of the fitted parameter R_{ct} increased and C_{dl} decreased. The corrosion inhibitors replaced water on the metal surface and were adsorbed to the film. The adsorption of the two corrosion inhibitors on metal surface obeyed the Langmuir isothermal adsorption equation. According to SEM and XPS analysis, the molecules of corrosion inhibitors could form covalent bonds with metal by N atom and could be adsorbed to the film on the metal surface. IM and IU have corrosion inhibition effects on carbon steel and IU has stronger inhibition effect. Both corrosion inhibitors are mixed type corrosion inhibitors and have high corrosion resistance to the cathode. The adsorption of these two compounds on the surface of carbon steel is spontaneous exothermic process and the adsorption rules are in accordance with the Langmuir isothermal adsorption which belongs to single molecular layer adsorption.

KEY WORDS: imidazolidinyl urea; corrosion inhibitor; HCl corrosion; carbon steel; electrochemistry; adsorption

钢铁结构表面的锈迹通常使用盐酸去除,但在酸性环境下,钢铁材料不可避免地发生腐蚀溶解现象^[1-2]。在清洗液中加入缓蚀剂能够有效减缓或阻止金属的过度消耗。目前常用的缓蚀剂主要是分子结构中含有硫、氮等元素或芳环、不饱和键的有机化合物,分子中的不饱和键或杂原子能够提供活性吸附中心,使缓蚀剂分子吸附在金属表面,赋予化合物高效的缓蚀性能^[3-8]。

咪唑啉环具有 P- π 共轭特征,使咪唑啉类化合物能够吸附在金属表面形成吸附膜,在酸性环境中具有优异的缓蚀效果,在石油、化工、天然气等工业领域具有广泛的应用价值^[9]。然而,有研究发现,在某些情况下,添加缓蚀剂会引起局部腐蚀^[10-15]。Tan 等^[10]研究发现咪唑啉膜在碳钢表面形成具有局部孔隙的多层膜,导致膜电阻的降低。Garcia^[11]在研究羟乙基咪唑啉吸附膜时发现了类似的情况,这种小阳极大阴极的情况造成金属发生严重的阳极局部溶解。

为提高缓蚀剂分子与金属表面的吸附性能和覆盖率,减小孔隙率,本文筛选具有双咪唑啉环的咪唑啉基脲为缓蚀剂,通过失重实验和电化学实验对比研究其与咪唑啉在酸性环境中对碳钢的缓蚀性能,并通过扫描电镜和 X 射线光电子能谱明确缓蚀剂分子与碳钢表面 Fe 原子的吸附作用机理,并利用吸附等温方程建立缓蚀剂分子在碳钢表面的吸附模型。

1 试验方法

1.1 试剂及试样前处理

作为缓蚀剂使用的化合物为咪唑啉(IM)和咪唑啉基脲(IU),分别购自于阿拉丁试剂有限公司和 Alfa Aesar 化学有限公司。碳钢试片分别切割成边长

10 mm 的正方体和尺寸为 50 mm×25 mm×2 mm 的长方体,用于电极制作和失重实验。金属试样实验前用砂纸打磨至 1200#,随后依次在去离子水和乙醇溶液中超声清洗 10 min,氮气吹干备用。缓蚀剂溶于 1 mol/L 盐酸溶液中配制成浓度梯度为 0.1~10 mmol/L 的电解质溶液。

1.2 失重实验

失重实验分别在 25、35、45 °C 进行,腐蚀速率 C_{RW} (mg/(cm²·h))、表面覆盖率 θ 以及缓蚀效率根据下列公式进行计算:

$$C_{RW} = \frac{m_1 - m_2}{St} \quad (1)$$

$$\theta = \frac{C_{RW}^0 - C_{RW}}{C_{RW}^0} \quad (2)$$

$$\eta_w = \frac{C_{RW}^0 - C_{RW}}{C_{RW}^0} \times 100\% \quad (3)$$

式中: m_1 和 m_2 分别为实验前后试样的质量; S 为试样的表面积; t 为浸泡时间; C_{RW}^0 和 C_{RW} 分别为添加缓蚀剂前后的腐蚀速率。

1.3 电化学测试

电化学实验采用三电极系统,在荷兰 IviumSTAT.h 电化学工作站上进行,以碳钢电极为工作电极,铂电极为辅助电极,饱和甘汞电极为参比电极。动电位极化曲线测试的扫描速率为 5 mV/s,扫描范围-700~-200 mV。缓蚀效率通过公式(4)计算:

$$\eta_i = \frac{J_{corr}^0 - J_{corr}}{J_{corr}^0} \times 100\% \quad (4)$$

式中: J_{corr}^0 和 J_{corr} 分别为添加缓蚀剂前后的腐蚀电流密度。

电化学交流阻抗谱测试采用的正弦波振幅为 10 mV, 测试频率范围为 100 kHz~10 mHz, 阻抗谱数据通过 ZSimpWin 软件进行等效电路拟合分析。其中缓蚀效率的计算公式为:

$$\eta_R = \frac{R_{\text{corr}} - R_{\text{corr}}^0}{R_{\text{corr}}} \times 100\% \quad (5)$$

式中: R_{ct}^0 和 R_{ct} 分别为添加缓蚀剂前后的电荷转移电阻。

1.4 表面分析

将碳钢试片逐级打磨抛光, 依次用去离子水和丙酮清洗后浸入加有缓蚀剂的盐酸溶液中, 室温浸泡 3 h, 然后取出试片, 依次用去离子水和乙醇冲洗试样表面, 氮气吹干。采用扫描电子显微镜 (TEDCAN VEGA 3 SBH 型), 在 20 kV 加速电压下, 对试样进行表面形貌观察。利用 PHI-5400 型 X 射线光电子能谱进行表面元素分析。

2 结果与讨论

2.1 失重实验

通过失重法研究了 25、35、45 °C 时不同浓度 IM、IU 在 1 mol/L HCl 溶液中对碳钢的缓蚀作用。根据公式(1)~(3)计算得到的腐蚀速率、覆盖度、缓蚀率等参数列于表 1。从表 1 中可以看出, 随着缓蚀剂浓度

表 1 碳钢在不同温度下浸泡在添加缓蚀剂前后的 1 mol/L 盐酸溶液中的腐蚀数据

Tab.1 Corrosion parameters of carbon steel immersed in 1 mol/L HCl solution at different temperatures before and after the corrosion inhibitors are added							
T/K	c/(mmol·L ⁻¹)	IM			IU		
		$C_{\text{RW}}/(\text{mg} \cdot \text{cm}^{-2} \cdot \text{h}^{-1})$	θ	$\eta_{\text{w}}/\%$	$C_{\text{RW}}/(\text{mg} \cdot \text{cm}^{-2} \cdot \text{h}^{-1})$	θ	$\eta_{\text{w}}/\%$
298	0	12.54			12.54		
	0.1	8.839	0.30	29.5	6.614	0.47	47.3
	0.5	8.341	0.33	33.5	2.503	0.80	80.1
	1	7.077	0.44	43.6	1.153	0.91	90.8
	5	5.62	0.55	55.2	0.284	0.98	97.8
	10	5.132	0.59	59.1	0.145	0.99	98.9
308	0	14.73			14.73		
	0.1	10.91	0.26	25.9	9.654	0.34	34.5
	0.5	10.18	0.31	30.9	5.503	0.63	62.6
	1	9.317	0.37	36.7	2.431	0.83	83.5
	5	7.187	0.51	51.2	1.469	0.90	90.0
	10	6.628	0.55	55.0	0.945	0.94	93.6
318	0	16.81			16.81		
	0.1	14.36	0.15	14.6	11.61	0.31	30.9
	0.5	12.67	0.25	24.6	9.229	0.45	45.1
	1	11.24	0.33	33.1	6.344	0.62	62.3
	5	8.654	0.49	48.5	2.644	0.84	84.3
	10	7.996	0.52	52.4	1.966	0.88	88.3

的提高, 缓蚀效率逐渐增加, 同一添加浓度, 咪唑啉基脲的缓蚀效率明显大于咪唑啉。随着温度的升高, 缓蚀剂分子在金属/溶液表面的吸附速率降低, 脱附速率升高, 从而导致缓蚀剂分子在金属表面的覆盖度降低, 效率随之减少^[16-18]。

2.2 电化学测试

2.2.1 动电位极化曲线

碳钢在 1 mol/L 盐酸中的 Tafel 极化曲线如图 1 所示, 通过拟合得到的电化学参数列于表 2。随着缓蚀剂加入腐蚀介质中, 腐蚀反应受到抑制, 腐蚀电流密度迅速降低, 且腐蚀电流密度随浓度的增加而逐渐减小, 缓蚀效率随之而逐渐增加, 这是由于缓蚀剂分子在此浓度下能够最大范围地覆盖碳钢表面^[19,20]。

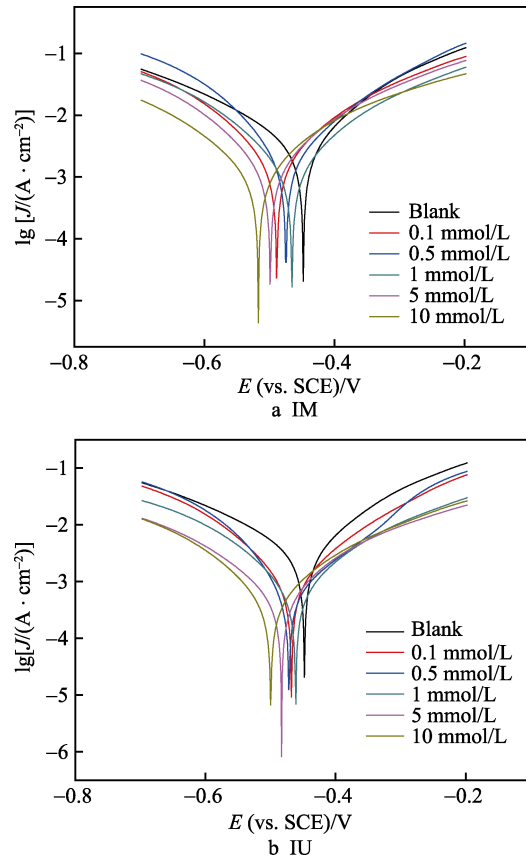


图 1 碳钢在含有缓蚀剂的盐酸溶液中的极化曲线
Fig.1 Polarization curves of carbon steel in HCl solution with corrosion inhibitors

从图 1 可以看出, 添加不同浓度缓蚀剂后的腐蚀电位与空白试验腐蚀电位之差小于 85 mV, 因此可以判断该缓蚀剂属于混合型缓蚀剂^[21-22]。阴、阳极腐蚀电流密度随着浓度的增加而降低, 阴极电流密度降低更明显, 说明缓蚀剂作为混合型缓蚀剂, 主要通过抑制腐蚀反应的阴极析氢反应来减缓碳钢的腐蚀过程。Tafel 曲线斜率没有明显变化, 说明缓蚀剂的加入并没有改变腐蚀反应的机理, 仅仅是通过缓蚀剂分子吸

表 2 碳钢在添加缓蚀剂前后的 1 mol/L 盐酸溶液中的极化曲线参数
Tab.2 Polarization parameters of carbon steel immersed in 1 mol/L HCl solution before and after corrosion inhibitors are added

Inhibi- tor	<i>c</i> /(mmol· L ⁻¹)	<i>E</i> (vs. SCE)/V	<i>J</i> (mA· cm ⁻²)	<i>β</i> _c /(mV· dec ⁻¹)	<i>β</i> _a /(mV· dec ⁻¹)	<i>η</i> _i /%
Blank	0	-448	1.156	-20.2	22.1	
IM	0.1	-493	1.011	-19.9	21.5	12.5
	0.5	-472	0.631	-21.2	22.3	45.4
	1	-464	0.398	-18.5	24.1	65.6
	5	-502	0.345	-23.6	20.8	70.2
	10	-516	0.316	-20.7	19.8	72.7
IU	0.1	-472	0.372	-17.3	18.3	67.8
	0.5	-477	0.317	-19.6	21.3	72.6
	1	-468	0.224	-22.6	22.5	80.6
	5	-488	0.174	-21.0	20.9	84.9
	10	-509	0.158	-23.8	21.6	86.3

附在碳钢表面形成一层保护膜，封闭碳钢表面的活性点位^[23-24]。

2.2.2 电化学交流阻抗谱

碳钢在 1 mol/L HCl 溶液中的交流阻抗谱如图 2 所示，从图 2 可以看出，所有阻抗图均展现出一个单

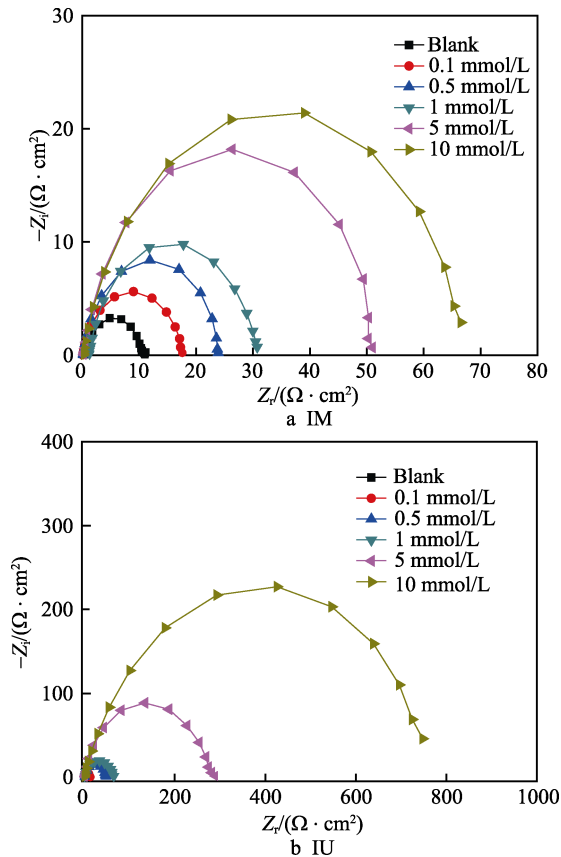


图 2 碳钢在含有缓蚀剂的盐酸溶液中的 Nyquist 图
Fig.2 Nyquist plots of carbon steel in HCl solution with corrosion inhibitors

一容抗，说明碳钢在盐酸溶液中的腐蚀行为受到电荷转移过程的控制。随着缓蚀剂的加入，没有改变容抗弧的形状，仅仅改变容抗弧的大小，说明缓蚀剂的加入没有改变反应机理，仅仅通过抑制腐蚀反应过程中电荷转移过程来延缓腐蚀^[25]。容抗弧不是一个完整的半圆，这主要是由于碳钢电极表面的粗糙度和表面化学不均一性引起的^[26]。

交流阻抗谱根据图 3 所示的等效电路进行拟合，表 3 列出了溶液电阻、电荷转移电阻、双电层电容和缓蚀效率等交流阻抗谱拟合参数。碳钢表面的双电层可以看作是一个非理想电容，通过引入常相位角元件来代替电容元件。常相位角元件的阻抗通过公式(6)计算^[27]：

$$Q_{CPE} = Y_0^{-1} (j\omega)^{-n}$$
 (6)

式中：*j* 为虚数，*j*²=-1；*Y*₀ 为 CPE 常数；*ω* 为角频率；*f* 为频率；*n* 为表面不均匀程度^[28]。根据 *n* 值的不同，CPE 可以代表电阻（*n*=0，*Y*₀=*R*）、电容（*n*=1，*Y*₀=*C*）、电感（*n*=-1，*Y*₀=*L*）或韦伯阻抗（*n*=0.5，*Y*₀=*W*）。此外，双电层电容 *C*_{dl} 用公式(7)进行计算^[29]：

$$C_{dl} = Y_0 (\omega_m)^{n-1}$$
 (7)

式中：*ω*_m 为角频率在虚部的最大值，*ω*_m=2*πf*_{max}。

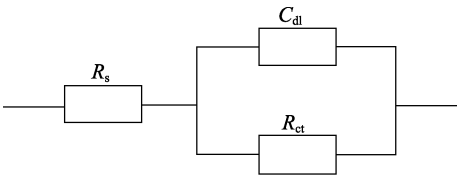


图 3 等效电路图
Fig.3 Equivalent circuit diagram

从表 3 可以看出，*R*_{ct} 值随着缓蚀剂浓度的增加而增大，说明随着缓蚀剂分子在碳钢表面的吸附，腐

表 3 碳钢在添加缓蚀剂前后的 1 mol/L 盐酸溶液中的交流阻抗谱参数
Tab.3 EIS parameters of carbon steel immersed in 1 mol/L HCl solution before and after corrosion inhibitors are added

Inhibitor	<i>c</i> /(mmol· L ⁻¹)	<i>R</i> _s /(Ω· cm ²)	<i>C</i> _{dl} /(μF· cm ⁻²)	<i>n</i>	<i>R</i> _{ct} /(Ω· cm ²)	<i>η</i> _R /%
Blank	0	0.9591	266	0.86	9.681	
IM	0.1	1.235	190	0.92	18.26	47.0
	0.5	1.195	149	0.94	22.25	56.5
	1	1.059	127	0.91	33.73	71.3
	5	1.182	116	0.95	52.91	81.7
	10	1.117	95	0.92	69.93	86.2
IU	0.1	1.19	228	0.98	12.23	20.8
	0.5	1.15	186	0.95	46.99	79.4
	1	1.29	137	0.98	61.66	84.3
	5	1.25	98	0.96	270.2	96.4
	10	1.003	43	0.97	735.9	98.7

蚀反应进行的难度增大,双电层电容的减小说明原本吸附在碳钢表面的具有较大介电常数的水分子被分子体积更大、介电常数更低的缓蚀剂分子所代替。IU的缓蚀效率大于IM,说明所选用的缓蚀剂较咪唑啉分子能够提供更强的吸附中心和更完善的保护层。

2.3 吸附等温模型

通过失重实验和电化学实验推断,缓蚀剂分子通过吸附在溶液/金属界面起到缓蚀作用,因此,吸附等温模型能够提供缓蚀剂分子和金属表面的相互作用机理^[30-31]。极化曲线的数据说明,缓蚀剂在金属表面的吸附符合Langmuir吸附等温式,该模型假设金属表面存在一定的吸附活性点位,每个活性点位能够固定一个吸附分子^[32]。根据这个模型,表面覆盖率与缓蚀剂浓度相关,根据Langmuir吸附等温式(公式8),以 c/θ 对 c 作图,如图4所示,得到的拟合直线斜率为1,线性系数 $R^2 > 0.99$,说明缓蚀剂的吸附符合Langmuir吸附等温模型。

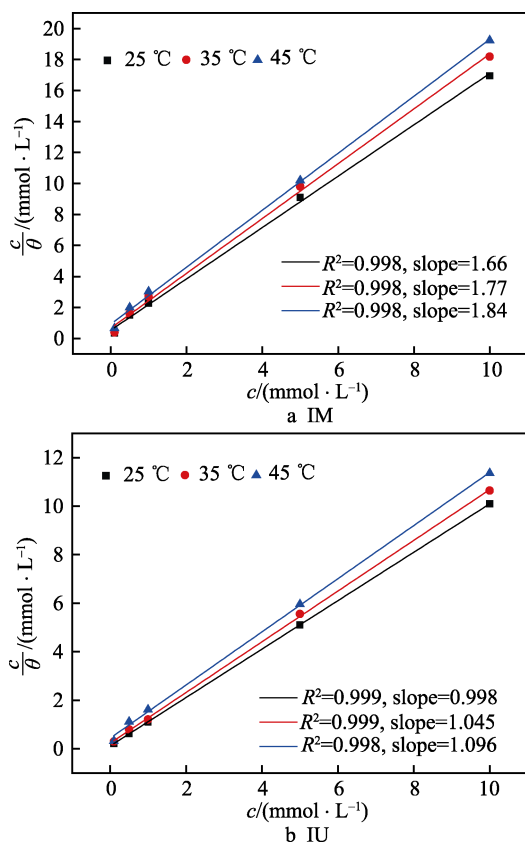


图4 碳钢在盐酸溶液中的Langmuir吸附等温式
Fig.4 Langmuir adsorption isotherms of carbon steel in HCl solution

$$\frac{c}{\theta} = \frac{1}{K_{\text{ads}}} + c \quad (8)$$

式中: c 为缓蚀剂浓度; θ 为表面覆盖率,通过失重实验数据计算; K_{ads} 为吸附平衡常数,根据图5所得直线截距计算。标准吸附吉布斯自由能与吸附平

衡常数 K_{ads} 相关,通过公式(9)计算:

$$\Delta G_{\text{ads}}^{\ominus} = -RT \ln(55.5 K_{\text{ads}}) \quad (9)$$

式中: R 为气体常数; T 为温度;55.5为水在溶液中的摩尔浓度。通过计算得到的 K_{ads} 和 $\Delta G_{\text{ads}}^{\ominus}$ 列于表4。吸附过程的焓变和熵变根据公式(10),以 $\ln K_{\text{ads}}$ 对 $1/T$ 作图,通过斜率计算吸附过程的焓变,根据截距得到吸附过程的熵变。

$$\ln K_{\text{ads}} = \ln \frac{1}{55.5} - \frac{\Delta G_{\text{ads}}^{\ominus}}{RT} + \frac{\Delta S_{\text{ads}}^{\ominus}}{R} \quad (10)$$

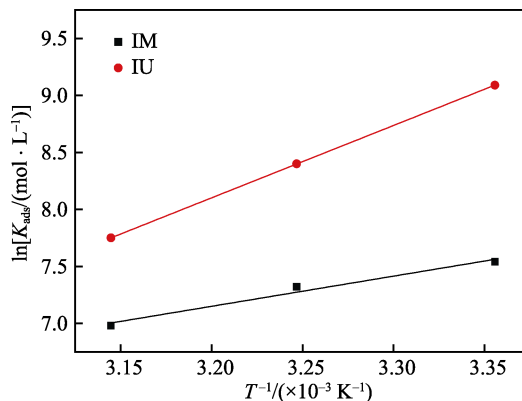


图5 IM和IU的 $\ln K_{\text{ads}} - 1/T$ 图
Fig.5 Plot of $\ln K_{\text{ads}} - 1/T$ of IM and IU

表4 缓蚀剂在碳钢表面的吸附热力学函数
Tab.4 Adsorption thermodynamic parameters of corrosion inhibitors on carbon steel surface

Inhibitor	T/K	$K_{\text{ads}}/(\times 10^4 \text{ L} \cdot \text{mol}^{-1})$	$\Delta G_{\text{ads}}^{\ominus} / (\text{kJ} \cdot \text{mol}^{-1})$	$\Delta H_{\text{ads}}^{\ominus} / (\text{kJ} \cdot \text{mol}^{-1})$	$\Delta S_{\text{ads}}^{\ominus} / (\text{kJ} \cdot \text{mol}^{-1})$
IM	298	1.88	-28.6		
	308	1.51	-29.0	-22.0	22.4
	318	1.08	-29.1		
IU	298	8.88	-32.5		
	308	4.45	-28.9	-52.8	-68.2
	318	2.31	-31.1		

K_{ads} 说明了吸附能力的强弱,数值越大说明缓蚀剂分子与金属表面的吸附速度越快且牢固。当 $\Delta G_{\text{ads}}^{\ominus}$ 值小于-20 kJ/mol,说明缓蚀剂分子与金属表面存在静电作用,属于物理吸附。 $\Delta G_{\text{ads}}^{\ominus}$ 值接近-40 kJ/mol,说明电子从缓蚀剂分子转移到金属表面形成共价键,属于化学吸附^[33-35]。从表4中数据可以看出,缓蚀剂的 $\Delta G_{\text{ads}}^{\ominus}$ 绝对值在28~34之间,说明缓蚀剂在金属表面的吸附过程是自发过程,同时兼具物理吸附和化学吸附。吸附的焓变 $\Delta H < 0$,说明吸附过程是放热反应,因此升高温度不利于缓蚀剂分子的吸附。吸附过程的熵变 $\Delta S < 0$,说明缓蚀剂分子有序地吸附在金属表面代替了表面的水分子,使无序程度减小^[36]。

2.4 表面形貌表征

金属试块的表面形貌如图6所示,实验前经打磨

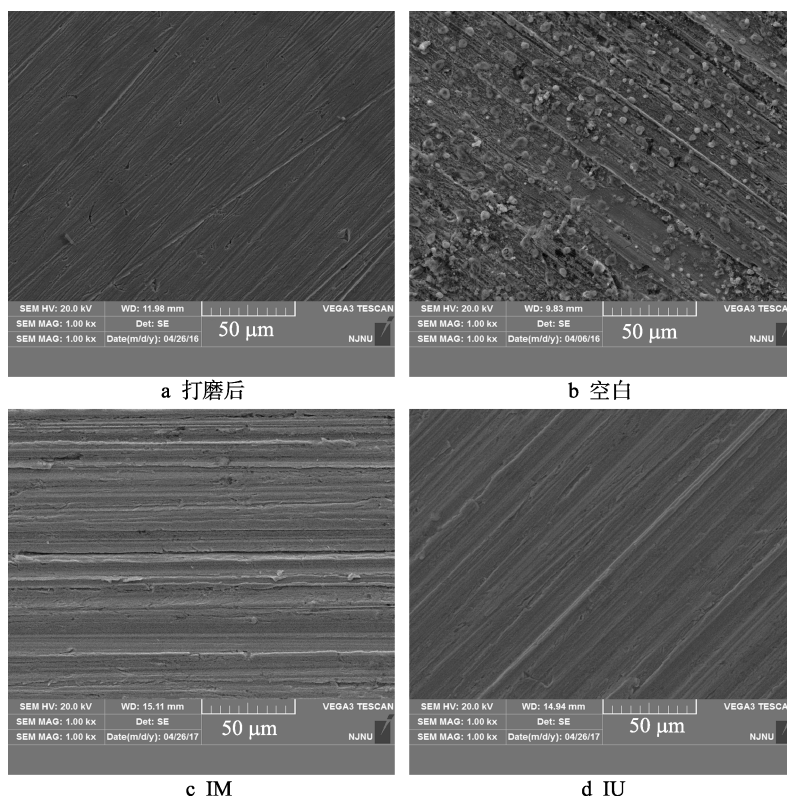


图 6 碳钢在添加缓蚀剂的盐酸溶液中的 SEM 图

Fig.6 SEM of carbon steel immersed in HCl solution with corrosion inhibitor: (a) after abrading, (b) blank, (c) IM, (d) IU

后的试样表面平滑、无腐蚀 (图 6a), 浸没于无缓蚀剂的 1 mol/L 盐酸中 3 h 后, 表面发生严重腐蚀 (图 6b)。而添加缓蚀剂后, 腐蚀程度显著减小, 其中试样在添加 IU 的溶液中的腐蚀程度明显低于在添加 IM 的溶液中。这说明添加 IU 在碳钢表面形成的保护膜较添加 IM 时具有更优异的保护效果。

碳钢试片浸没在含有缓蚀剂的盐酸溶液中 24 h 后, 通过 XPS 研究缓蚀剂在碳钢表面的吸附成膜机理。从谱图中可以看出, 在碳钢表面分别检测出 C、N、O 的谱峰。C 1s、N 1s、O 1s、Fe 2p 高分辨峰如图 7 所示。

缓蚀剂在碳钢表面的 C 1s 谱由两个峰组成。在

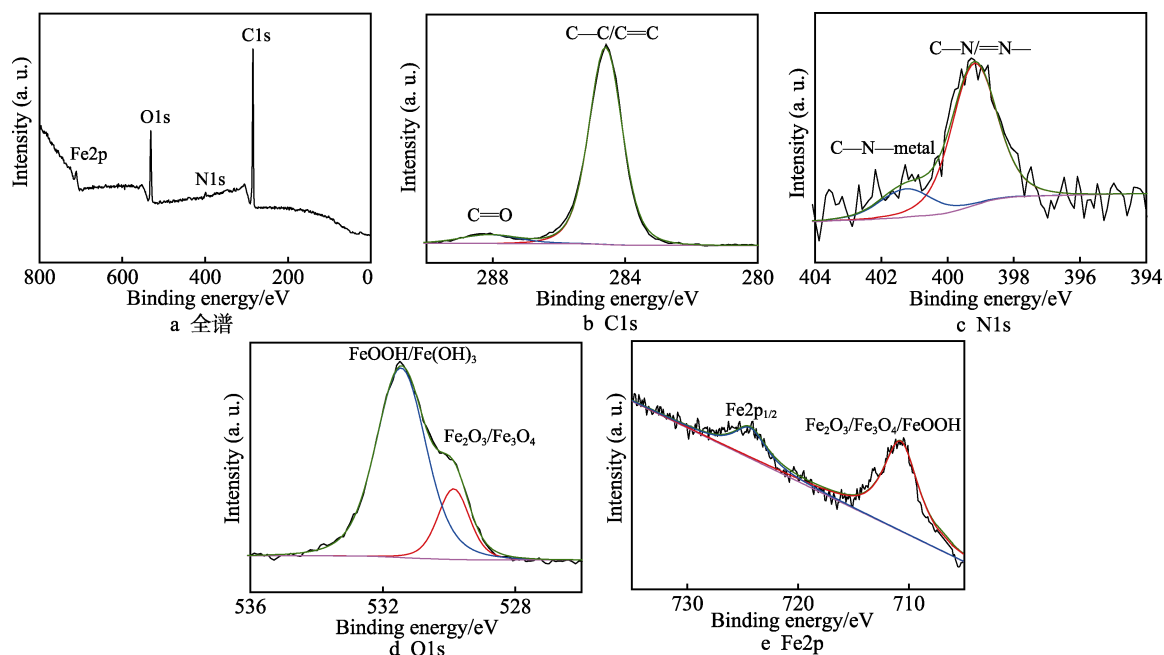


图 7 碳钢在添加 IU 的盐酸溶液中的 XPS 图

Fig.7 XPS deconvoluted profiles for survey (a), C 1s (b), N 1s (c), O 1s (d) and Fe 2p (e) for carbon steel immersed in HCl with IU

284.6 eV 处的最大峰可以看作是杂环上的 C—C、C=C 以及 C—H 键的特征结合能。288 eV 处的特征峰可以认为是 C=O 键的 C 原子结合能^[37-38]。N1s 谱由 2 个峰组成, 第一个峰处于结合能 399.2 eV 处, 这个峰可以认为是咪唑环上的 C—N 键以及非质子化的 N 原子^[39-40]。在 401.2 eV 处的第二个峰为咪唑环上的 N 原子与 Fe 原子形成的配位键^[41-43]。O 1s 谱包括 2 个峰, 结合能为 529.9 eV 处的峰原则上来源于 O²⁻与 Fe³⁺形成的 Fe₂O₃ 或 Fe₃O₄ 化合物的结合能^[44], 531.5 eV 处的峰来源于 FeOOH 或 Fe(OH)₃ 中的 OH⁻。Fe2p 谱在 710.7 eV (Fe2p_{3/2}) 和 724.3 eV (Fe 2p_{1/2}) 有两个峰, 主要为铁的氧化物和氢氧化物。在 710.7 eV 处为 Fe(III) 的化合物, 包括 FeOOH、Fe₂O₃、Fe₃O₄ 等^[45-46]。根据 XPS 测试结果可以判断出, 缓蚀剂能够吸附在碳钢表面形成吸附膜。

3 结论

1) 在不同温度下, 两种咪唑啉化合物加入腐蚀介质中能够有效降低碳钢的腐蚀速率, 且咪唑啉基脒的缓蚀作用更好。

2) 两种化合物均属于混合型缓蚀剂, 主要通过咪唑啉环及 N 原子与金属形成配位键, 吸附在金属表面, 抑制腐蚀反应的进行。

3) 缓蚀剂分子在腐蚀介质中自发地吸附在碳钢表面形成单分子层吸附膜, 吸附符合 Langmuir 吸附等温模型。

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