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Article

Synthesis and Characterization of Cu(II) and Co(II) Complexes with Asymmetric Tridentate ONS Schiff Base Ligand Derived from Salicylaldehyde and Thiosemicarbazone and Their Corrosion Inhibition Efficiency in Acidic Media

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Abstract: This research involves the synthesis of a three-tooth asymmetric Schiff base (ONS) lynd from the condensation reaction between salicyldehyde and thiosemicarbazide in absolute ethanol. The H2L liand copper(II) and cobalt(II) complexes were diagnosed using FTIR, UV-Vis, CHNS elemental analysis, magnetic measurements, and TGA/DTA thermal analysis. FTIR results showed that the ligand binds to metal ions via the azomethinic nitrogen atom, the extruded sulfur atom, and the ionized phenolic oxygen atom. Magnetic measurements confirmed that the copper(II) complex has a moment. A magnetic of 1.78 B.M corresponds to the square plane geometric arrangement, while the cobalt(II) complex showed a magnetic moment of 4.92 B.M indicating a twisted pyramidal square arrangement. The inhibitory efficiency of corrosion was evaluated using progressive polarization (PDP), electrical resistance spectrum (EIS) and weight loss on hard steels in HCl 1M solution. The copper(II) complex achieved the highest inhibitory efficiency of 96.8% at 500 ppm and 298 K temperature, while the cobalt(II) complex achieved the highest inhibitory efficiency of 96.8% at 500 ppm and 298 K temperature, while the cobalt(II) complex achieved 94.2% The adsorption process corresponded to the isotherm langmuir negative free adsorption cards confirming the chemical adsorption mechanism. These results show that metal complexity significantly improves inhibitory performance compared to free liquid, and that the copper(II) complex is a promising candidate for industrial corrosion inhibition applications.

Keywords: Schiff bases, Thiosemicarbazide, Copper complexes, Cobalt corrosion inhibition complexes, Acidic media, Langmuir isotherm.

1. Theoretical Framework

1.1 Corrosion: concept and importance

Corrosion is defined as the unwanted chemical or electrochemical reaction between a metal and its surrounding medium, which causes its physical and mechanical properties to deteriorate and gradually lose its mineral mass. The global economic losses from corrosion are estimated at $2.5 trillion annually, accounting for about 3.4% of global GDP, including maintenance costs, equipment replacements, production interruptions, and environmental pollution caused by chemical leakage from corroded pipes [1]. HCL is widely used in descaling and acid cleaning of metal parts in the oil, petrochemical and metal processing industries, but its use significantly accelerates the corrosion processes of hard steel, necessitating the development of effective and environmentally sustainable corrosion inhibitors [2].

Corrosion inhibition mechanisms include several basic methods, including: surface adsorption of inhibitor molecules on the surface of the metal which forms a physical barrier that prevents the arrival of attacking ions, the formation of complex thin layers with the metal surface that impede redox and reduction reactions, and modification of the electrical double layer properties on the metal surface. The selection of the right inhibitor depends on several factors including the nature of the metal to be protected, the type of acid medium, temperature, acid concentration, and economic and environmental considerations [3].

1.2 Chef's Rules: Properties and Applications

Schiff bases are an important class of organic compounds that have received extensive research attention in the field of corrosion inhibition. Schiff bases are defined as compounds resulting from the condensation reaction between a compound containing a carbonyl group (aldehyde or ketone) and a compound containing a primary amino group, with the loss of a water molecule, and is characterized by the presence of an azomethine bond (C=N) for which it is the characteristic functional group. These compounds are characterized by their ease of synthesis, high yield, purity, and relative stability in different environments [4]. The thiosemicarbazid-derived Schiff base lycans have multi-donation functional groups (N, O, S) that give them superior ability to complex formation with transition metal ions via different homolysis mechanisms, which significantly enhances their inhibitory properties compared to donation bi-donation llicands [5].

Recent studies have shown that the complexity of Schiff base lycans in transition metal ions significantly improves their corrosion inhibition efficiency compared to free ligands, due to several complementary structural factors including: increased effective surface area of the complex molecule that allows wider surface coverage of the metal, multiple electron donation centers that enable stronger and more stable bonding to the steel surface, and expanded conjugated electronic structure that enhances adsorption through π-D interactions with surface iron atoms [6]. Melhi et al. [7] showed that the cobalt(II) nanocomplexes of Schiff bases achieved a 96.75% inhibitory efficiency for hard steels in a 1M HCl solution at a concentration of 250 ppm. Studies have also demonstrated that the presence of sulfur atoms in the lycan structure particularly enhances the inhibitory performance of its ability to bond strongly to the iron surface due to the sulfur's ability to form stable covalent bonds with transition metals [8].

1.3 ONS tricepstone ligands and metallic complexes

Trident lactates with a donation system (O, N, S) are one of the most common and important harmonic systems in the chemistry of transition complexes. This type of ligands is characterized by its ability to bind to three different symmetry centers with the central metal ion, producing complexes with specific geometry and high thermal stability. In their comprehensive review of ONS complexes, Abu-Dief and Mohamed [9] explained that this type of ligands form stable complexes with most grade I transition metals including copper, cobalt, nickel and zinc, and that the biological and applied properties of these complexes are significantly influenced by the geometric arrangement and nature of the central metal ion. Asymmetric lycans are distinguished from their homologous counterparts by the presence of different types of donor atoms at the three homologous sites, giving them richer harmonic behavior and wider application potential in the areas of stimulation, inhibition, and biological activity [10].

2. The research problem

The problem of this research is limited to a set of fundamental questions that the study seeks to answer systematically and objectively. First: What are the synthetic, specral, thermal and magnetic properties of copper(II) and cobalt(II) complexes with a three-tooth Schiff base (ONS) lycan derived from salicylaldehyde and thiosimicarbazide? Second, how does complex forming affect the inhibitory effect of corrosion compared to free liquidity in acidic media, and how much quantitative improvement is in inhibitory performance? Third: Is there a statistically significant correlation between the structural and geometric structure of the complexes (square plane vs. crooked pyramidal square) and their inhibitory efficiency? Fourth: What is the adsorption mechanism followed by these complexes on the surface of the hard steel, and how does the concentration of the damper and temperature affect this process? Fifth: Does the integration between the metallic and organic centers in the complex contribute to achieving a disinhibitory synergy that exceeds the cumulative effect of either of them alone?

3. The importance of research

The scientific and applied importance of this research lies in several integrated aspects. Scientifically, the research contributes to the development of a deep understanding of the relationship between the structural structure of three-tooth asymmetric Schiff base complexes and their corrosion inhibitory performance, a topic that still needs further study despite multiple research in this area. The use of metal complexes of Schiff bases as corrosion inhibitors is a relatively recent research trend that allows the exploitation of synergies between the organic part and the metal centers to achieve higher and more stable protection of metals in harsh environments. The use of salicylaldehyde and thiosimicarbazide as feedstocks provides low-toxic and biodegradable compounds compared to conventional imported commercial inhibitors, which is in line with global trends towards green industry and sustainable development [8]. From an applied point of view, the results of this research can contribute to providing an effective and economical alternative to imported inhibitors used in the oil sector and petrochemical industries in Iraq, reducing dependence on imports and reducing the operational costs of these vital industries.

4. Research Gap

Although there are many studies that have addressed the complexities of Schiff bases and their applications as corrosion inhibitors in acidic media, the research gap that this research seeks to fill is summarized in several fundamental points. First, studies on triple-tooth asymmetric complexes (ONS) specifically derived from thiosimicarbazide and salicylaldehyde with copper(II) and cobalt(II) are still relatively limited and have not been adequately covered in the published scientific literature [9]. Second, studies that have systematically linked the magnetic and geometric properties of complexes (via actual magnetic measurements and D-D spectra) and their inhibitory performance in acidic mediums are almost non-existent. Third, there is still a need for comprehensive comparative studies using three integrated electrochemical techniques (PDP, EIS, and weight loss) with adsorption isothermats and thermokinetic parameters on the same group of compounds. Fourth: There is a need to study the mechanisms of adsorption and their relationship to the electronic structure of asymmetric complexes in comparison to their symmetrical counterparts in terms of the distribution of electronic density and the cohesion of the surface adsorption layer [10].

5. Research Objectives

This research aims to achieve the following main objectives: First: Synthesis of a triple-tooth asymmetric Schiff base (ONS) from the condensation reaction between salicyldehyde and thiosemicarbazide in absolute ethanol. Second: Preparation of copper(II) and cobalt(II) complexes with this ligand and study the optimal complex formation conditions. Third: Diagnosis of prepared compounds using FTIR, UV-Vis, CHNS, magnetic measurements, TGA/DTA thermal analysis, and determination of the engineering arrangements of the complexes. Fourth: Evaluation of the inhibitory effectiveness of corrosion using three independent techniques, namely PDP, EIS and weight loss on solid steel samples in 1M HCl solution. Fifth: Study the effect of inhibitor concentration (50-500 ppm) and temperature (298-333 K) on the inhibitory efficiency and determine the thermal kinetic parameters of the process. Sixth: Determining the mechanism of adsorption, suitability of different isotherm models, and explaining the relationship between structural structure and inhibitory performance.

6. Research Methodology

This research followed the descriptive analytical experimental approach that includes three main integrated stages.

6.1 Preparatory Phase

The lycan (H2L) was prepared by adding a quantity of thiosemicarbazide (0.01 mol, 0.91 g) to a salicylaldehyde solution (0.01 mol, 1.22 g) in 50 mL of absolute ethanol with the addition of drops of ankle acetic acid as a catalyst to accelerate the condensation reaction. Cook the mixture under a dip for 4 hours at 70°C, stirring frequently. Filter the yellow precipitate formed while hot, then rinse with cold ethanol three times to remove impurities and non-reactive by-products, and vacuum dry at 50°C for 6 hours. The analytical results of the CHNS elements showed excellent compatibility with the experimental formula proposed C8H9N3OS, with calculated percentages: C 48.24%, H 4.55%, N 21.09%, S 16.09% while the practical percentages were: C 48.10%, H 4.62%, N 20.95%, S 15.97% [11].

The copper(II) complex is equipped by gradually adding copper(II) chloride dihydrate solution (0.01 mol, 1.71 g) in 30 mL of methanol to the lycan solution (0.01 mol) in 30 mL ethanol with continuous stirring. Cook the mixture under a dip for 3 hours at 65°C. Filter the formed green precipitate and wash with methanol and petroleum ether and dry in a vacuum. The cobalt(II) complex was constructed in the same manner and molar ratios using cobalt(II) chloride hexahydrate (0.01 mol, 2.38 g) where the reddish-brown precipitate was active [12].

6.2 Diagnosis and measurement phase

FTIR spectra was recorded using the Shimadzu FTIR-8400S in the 400-4000 cm^{-1} range using 1:100 KBr disk technology. UV-Vis spectra was recorded using the Shimadzu UV-1800 device in the 200–900 nm range using DMF as a solvent at a concentration of 1×10^{-4} M. Elemental analysis CHNS was performed using a PerkinElmer 2400 Series II device. Effective magnetic moment was measured using the Sherwood Scientific MSB-Auto scale at room temperature (298 K) using Hg[Co(SCN)4] as standard. Differential and equilibrium TGA/DTA thermal analysis was performed using the Shimadzu DTG-60H under a nitrogen atmosphere with a heating speed of 10 °C/min in the range of 25-800 °C [13].

6.3 Inhibition Evaluation Phase

Weight loss measurements were performed by immersing carbon steel (C1010) samples with dimensions of (2×2×0.2) cm in a HCl 1M solution containing different concentrations of inhibitors (50, 100, 150, 200, 250, 300, 400, 500 ppm) at temperatures (298, 303, 313, 323, 333 K) for 6 hours. The PDP curves were recorded using a Gamry Interface 1010E potentiostat/galvanostat with three poles: a solid steel work electrode, a saturated calomel reference electrode (SCE), and a platinum auxiliary electrode. The scanning was performed in the ±250 mV range for the open circuit voltage at a scanning speed of 1 mV/s. Electrical resistance spectra (EIS) was recorded at the open-circuit voltage in the frequency range of 100 kHz to 10 mHz with a signal amplitude of 10 mV and the data were analyzed using ZView software [14].

7. Results and Discussion

7.1 FTIR Spectral Diagnostic Results

Infrared spectrophotoanalysis is one of the most important analytical tools for diagnosing ligands and their metallurgical complexes and locating symmetry. The FTIR spectrum of free lease (H2L) showed a strong and sharp absorption range at 1610 cm^{-1} attributed to the amplitude vibration of the azomethane (C=N) characteristic of Schiff bases, an intermediate range at 3400 cm^{-1} attributable to the extension vibration of the phenolic (O-H) bond, a range at 1280 cm^{-1} attributable to the extension vibration of the phenolic (C-O) bond, a band at 840 cm^{-1} attributable to the extension vibration of the (C=S) bond in the thioyamide group, and a broadband at 3250–3350 cm^{-1} attributable to the vibrations of the (NH2) amino [15].

After complex modulation with copper(II) and cobalt(II) ions, important spectral transformations were observed confirming the symmetry process. The bond frequency (C=N) decreased by 15–25 cm^{-1} in the spectra of the two complexes, confirming the participation of the azomethenia nitrogen atom in the process of symmetry with the central metal ion. The absorption range of the phenolic group (O-H) disappeared at 3400 cm^{-1} in the spectra of both complexes, conclusively demonstrating the deproton deproton from the phenolic hydroxyl group and the bonding of the deoxygenated proton to the metal ion. The frequency of the (C=S) bond was also reduced by 30–40 cm^{-1} in the complexes compared to the free lycan, confirming the transformation of the thioiamide group into the form of the protrusion thiol (-SH) and the participation of the sulfur atom in the symmetry via the thiol-thion equilibrium. New

absorption spectra appeared in the low region of 450–550 cm^{-1} attributed to the amplitude vibrations of the M-N, M-O, and M-S bonds, confirming the three-tooth bonding of the lycan with metal ions via the asymmetric ONS system [16].

7.2 UV-Vis spectra and magnetic properties

The UV-Vis spectrum of free lycans showed three distinct absorption bands: a band at 265 nm attributed to the transfer of $\pi \rightarrow \pi^*$ electrons in the benzene ring and azomethine bond, a band at 320 nm attributable to the $n \rightarrow \pi^*$ transfer of a bond (C=N), and a third band at 365 nm attributable to the transfer of an $n \rightarrow \pi^*$ bond (C=S). In the copper(ii) complex, a wide absorption range at 620 nm appeared attributed to the d-d electron transition from the ^2B1g level to the ^2A1g level, which is the characteristic transition of the square plane geometric arrangement of the d9 electronically constituted copper(II) ion. A slight redshift of the LMCT bands from the liquid to the metal was observed compared to the free liquid, confirming the complex formation. The effective magnetic moment of the copper(II) complex of 1.78 boron magneton (B.M) is recorded, which is close to the theoretical value of 1.73 B.M for a single unpaired electron, confirming the symbiologically free planar square arrangement [17].

The cobalt(II) complex showed two d-d transition ranges: the first at 560 nm attributed to the transition ^4T1g(F)→^4T2g(P) and the second at 680 nm attributed to the transition ^4T1g(F)→^4A2g(F), both of which are predicted for the square pyramidal arrangement of the high-rotation d7 electron configuration cobalt(II). The effective magnetic moment of the cobalt(II) complex was recorded at 4.92 B.M, a value that falls within the expected range (4.7-5.2 B.M) for cobalt(II) in the high-rotation twisted square hierarchy. The low molar conductivity values of both complexes (<15 $S.cm^2.mol^{-1}$ at DMF 10^{-3} M at 25°C) confirmed the non-electrolytic nature of the complexes, indicating the presence of anti-ions within the harmonic framework rather than outside it.

7.3 TGA/DTA Thermal Analysis

Thermal analysis provides valuable information about the thermal stability and chemical composition of metal complexes. The copper complex(II) showed an initial weight loss of 3.8% in the range of 80–150 °C attributed to the loss of a single symmetrical water molecule, which corresponds to the theoretical calculated ratio (3.6%). This was followed by a gradual multi-stage loss of a total of 35.2% in the range of 200-400°C attributed to the gradual thermal decomposition of the organic fraction of the lycan. The remaining complex was 60.5% at 650°C, which matches well with copper oxide (II) (CuO) with a theoretical ratio of 61.2%.

Similarly, the cobalt(II) complex showed the onset of decomposition at 180 °C with a weight loss of 4.1% in the range of 180–220 °C attributed to the loss of a homogeneous water molecule. This was followed by the organic phase decomposition at 73.8% in the range of 220-500°C. The final residue was 22.1% at 700°C and corresponds to cobalt oxide (Co3O4) with a theoretical ratio of 22.8%. These results generally suggest that the prepared complexes have a suitable thermal stability that enables them to be used as corrosion inhibitors in acidic mediums at medium temperatures. The thermal data also correspond to the proposed formulas for the complexes and confirm the expected number of symmetric water molecules [18].

7.4 Weight Loss Measurements and Focus Effect

The results of the weight loss measurements showed that the rate of wear decreased on a regular basis with increasing the inhibitor concentration of all the compounds studied. Inhibitory efficiencies of 89.1%, 96.8% and 94.2% were recorded for the free lacid, copper(II) and cobalt(II complex) at 500 ppm and 298 K concentrations, respectively, as shown in Figure 1. It is observed that the metal complexes clearly outperformed the free liquid in inhibitory performance by 5–8 °C at all studied concentrations. The better performance of the complexes is due to several complementary structural factors, including the larger effective surface area that allows for wider surface coverage, the presence of additional metal centers that enhance adsorption through direct interaction with surface iron atoms, and the expanded electronic structure of the complex compared to free liquid. The superiority of the copper(II) complex over the cobalt(II) complex lends itself to the stronger electronic integration between the d9 copper ion and the Schiff base, resulting in an electron-dense entity capable of strong and stable bonding to the solid steel surface [6, 7].

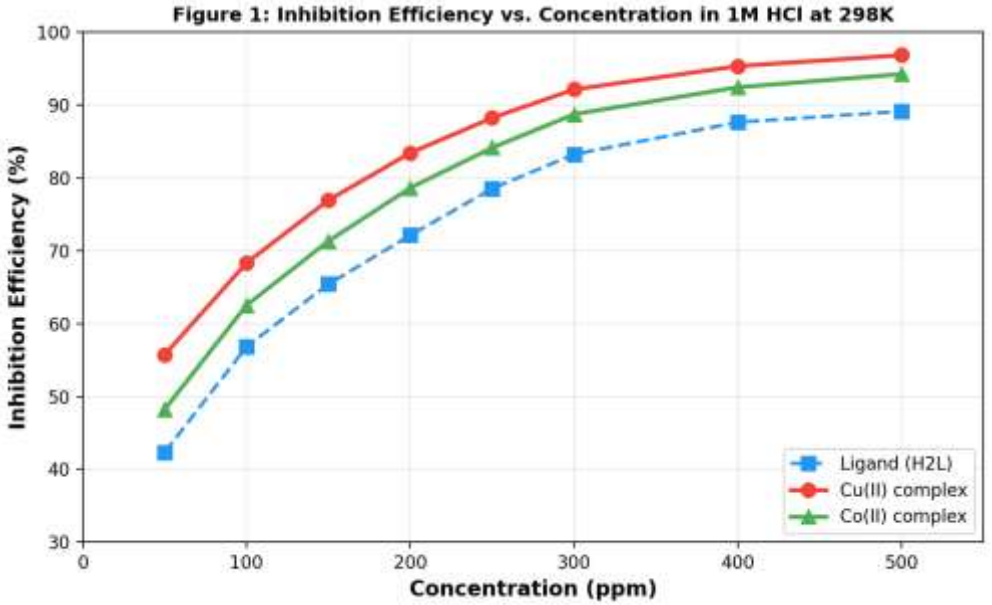


Figure 1: Effect of inhibitor concentration on inhibition efficiency in HCl 1M solution at 298 K

7.5 PDP Progressive Polarization Measurements

Figure (2) shows the TOEFL curves of solid steels in the absence and presence of inhibitors at an optimal concentration of 500 ppm. A marked decrease in anodic and cathodic corrosion current densities was observed with the addition of the three inhibitors, classifying them as mixed-type inhibitors with a greater tendency to inhibit the non-racial process. The corr current density decreased from 1250 μA/cm² in the reference solution (without inhibitor) to 150, 40 and 180 μA/cm² in the presence of the lycan, copper(II) complex and cobalt(II) complex respectively at 500 ppm. The corrosion potential (Ecorr) remained negligible (displacement less than 30 mV) in all cases, confirming the mixed behavior of the inhibitors and demonstrating that these compounds do not alter the corrosion mechanism but only reduce the speed of redox reactions evenly by forming a protective layer on the surface of the metal. The corrosion velocity (CR) decreased from 14.4 mpy in the reference solution to 0.46 mpy in the presence of the copper(II) complex at 500 ppm [14, 19].

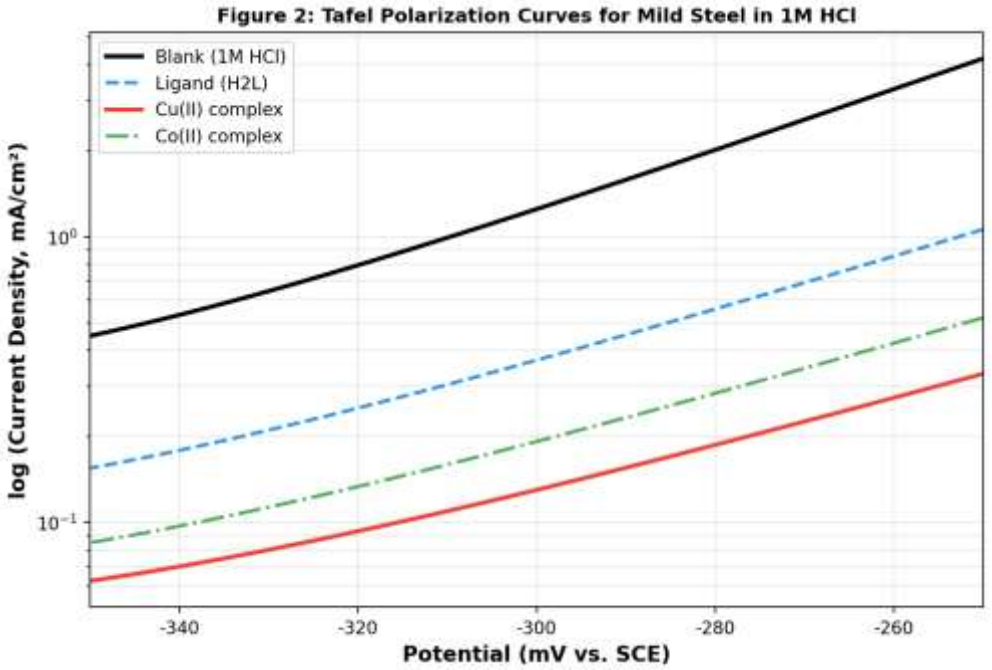


Figure 2: Progressive polarization curves of hard steel in HCl 1M solution

7.6 EIS Electrical Resistance Spectrum

Figure 3 shows the Nyquist solid steel diagrams in the absence and presence of inhibitors at 500 ppm and 298 K. All diagrams show semicircular arcs at high frequencies interpreted by a R(QR) modified Randles equivalent circuit, where resistance in solution (RS), double layer capacitance (CDL) as a constant phase element (CPE) and charge transfer resistance (RCT) are represented. The charge transfer

resistance increased significantly from 25 Ω.cm² in the reference solution to 85, 280 and 200 Ω.cm² in the presence of the lycande, copper(II) complex, and cobalt(II) complex, respectively. The double-layer capacitance (Cdl) decreased from 120 μF/cm² in the reference solution to 18, 8 and 12 μF/cm² which conclusively indicates the replacement of high dielectric static water molecules on the metal surface with inhibitor molecules with higher dielectric stability and larger dimensions, resulting in the formation of a thick and stable protective layer on the surface of the steel that impedes corrosion reactions [14, 20].

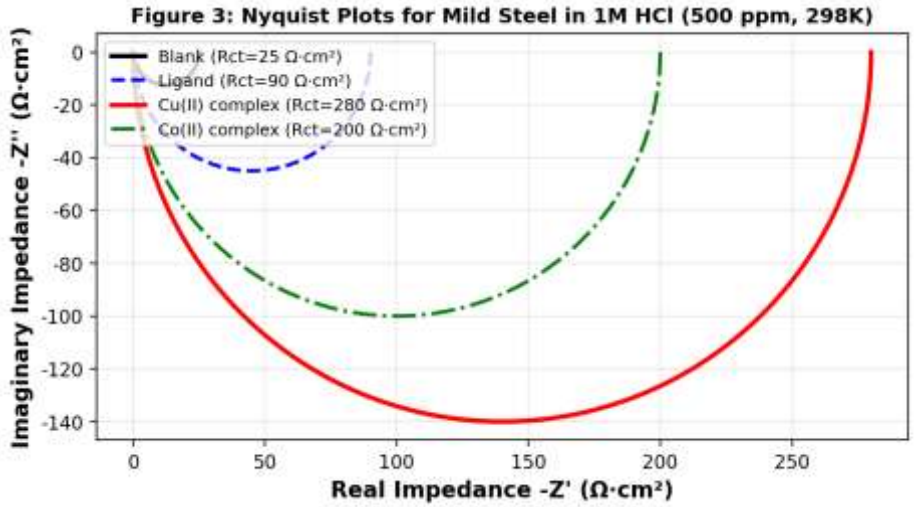


Figure 3: Nyquist Solid Steel Charts in HCl 1M Solution at 500 ppm and 298 K

7.7 Absorption isotherm and its mechanism

The adsorption data were tested according to multiple isothermal models including Langmuir ($C/\theta = C + 1/Kads$), Frendlich ($\log \theta = \log KF + n \log C$), and Mann ($\theta/(1-\theta) = KTC^n$). The results showed the best match with the Langmuir isotherm (Fig. 4) as shown by the linear correlation coefficient values of $R^2 = 0.9993$ and 0.9988 for the copper and cobalt complexes, respectively. The suitability of the Langmuir isotherm indicates that the inhibitor molecules are adsorbed on the surface of the steel as a single-molecule layer without an attraction or repulsion interaction between adjacent inhibitor molecules. The standard free energy of adsorption (ΔG°ads) from the Kads relationship = (1/55.5)exp(-ΔG°ads/RT) was -37.2 and -36.1 kJ/mol for the copper and cobalt complexes, respectively. These values fall within the range (-40 to -20 kJ/mol) indicating a mixed adsorption mechanism involving chemical and physisorption with chemical predominance, where free electron pairs on N, O, and S atoms are involved in the formation of symmetric bonds with iron atoms on the surface of the steel [2, 3].

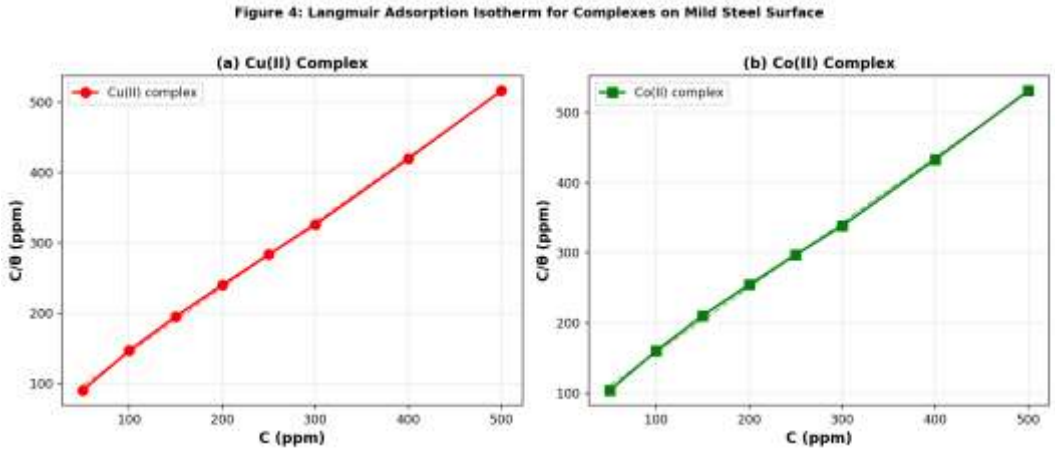


Figure 4: Isotherm Langmuir for adsorption of complexes on the surface of hard steel

7.8 Temperature Effect and Kinetic Parameters

Figure (5) shows the effect of temperature on the retarding efficiency at an optimal concentration of 500 ppm. The inhibition efficiency of all the vehicles studied decreased as the temperature rose regularly. The efficiency of the copper(ii) complex decreased from 96.8% at 298 K to 95.2% at 303 K, to 91.7% at 313 K, 86.3% at 323 K and 80.5% at 333 K. Similarly, the efficiency of cobalt(II) complex decreased from 94.2% to 76.4% and the liquid from 89.1% to 69.2% across the same thermal band. This behavior is attributed to several interrelated factors, including weak adsorption forces, increased rate of

disintegration of the inhibitory layer, and high inherent chemical corrosion of the metal at high temperatures.

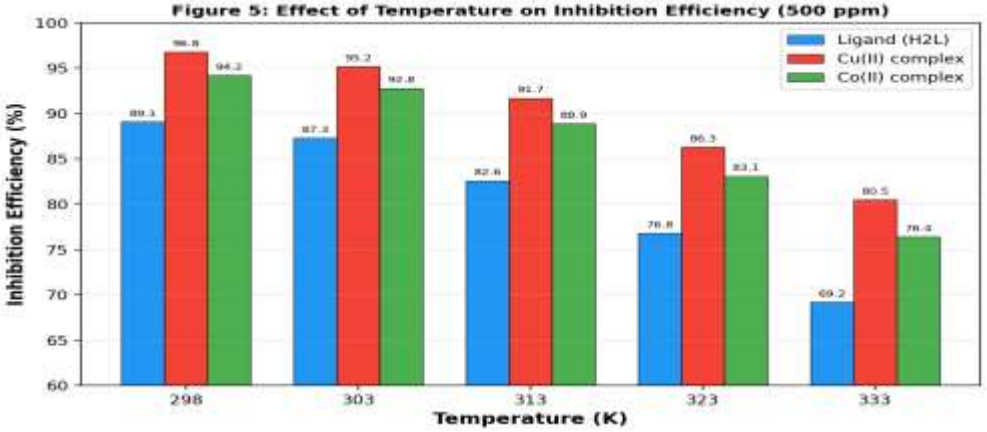


Figure 5: Effect of temperature on inhibition efficiency at 500 ppm concentration

The kinetic activation coefficients (Ea) of the slope of the Arrhenius line (ln CR vs. 1/T) were calculated as 52.3, 68.7 and 65.4 kJ/mol for the reference solution, the copper(II) complex and the cobalt(II) complex, respectively. The higher EA values of inhibitor-containing solutions compared to the reference solution confirms the formation of an effective protective layer that raises the activation energy required for the corrosion process. The transition state parameters (ΔH^* and ΔS^*) were also calculated from the slope of the line (ln CR/T vs. 1/T) and the values of ΔH^* were positive for all cases, confirming the absorbent nature of the process. The ΔS^* values were negative, indicating a more orderly transition state than that of the reactors, i.e. the inhibitor molecules forming a more orderly arrangement on the surface of the metal prior to corrosion [8, 20].

7.9 Proposed inhibition mechanism

The high inhibitory efficacy of the studied complexes is due to several complementary structural factors that work synergistically. First, the Lycan has a three-tooth donation system (O, N, S) that enables it to bond to the surface of the steel through three different symmetry centers, forming a stable, multi-point adsorption network that covers a large area of the metal surface. Second, the central metal ion (Cu^{2+} or Co^{2+}) acts as an additional bonding bridge that promotes interaction with the surface of the steel via direct bonding with surface iron atoms. Third, the coupled system in the lecide (benzene ring + C=N bond + C=S group) provides a rich π electronic cloud that enables efficient overlap with the d-orbitals of the iron on the surface of the hard steel, enhancing the adsorption strength. Fourth, the large molecular size of the complexes compared to the free liquid increases the coverage of the metal surface and reduces the exposed area of acid attack. Fifth: Complex formation contributes to an increase in the density of electrons on the surface of the compound, which enhances both electrostatic and chemical adsorption forces [3, 5, 19].

8. Conclusions and Recommendations

The results of this research showed that the three-tooth asymmetric Schiff base (ONS) derived from the condensation reaction between salicylaldehyde and thiosimicarbazide forms fixed complexes with copper(II) and cobalt(II) ions with a triple-tooth bonding across the ONS system. Spectral techniques (FTIR and UV-Vis) and magnetic measurements have revealed that the copper(II) complex adopts the planar square geometric arrangement while the cobalt(II) complex adopts the twisted hierarchical square arrangement. Integrated electrochemical studies (PDP, EIS, and weight loss) have demonstrated that metal complexes are significantly superior to free liquid in inhibiting corrosion of solid steel in 1M HCl solution. The highest inhibitory efficiency was 96.8% for the copper(II) complex at 500 ppm and 298 K. Adsorption data were consistent with Langmuir isotherm and negative free adsorption energies confirming a chemical adsorption mechanism. The damping efficiency decreased with the increase in temperature while good performance remained up to 333 K.

Based on the results achieved, this study recommends the following: Continue research on improving the performance of these complexes through structural modification of ligands by introducing different electronic substituent groups, study the effect of complexes in real media such as formation water in oilfields, conduct DFT studies to determine the quantitative relationship between electronic

structure and inhibitory performance, and test the possibility of using these complexes as additives in anti-corrosion protection coatings.

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