Effect of Corrosion in the CS Operation Indoors of the Electronics Industry in the Northwest of Mexico

Efecto de la corrosión en la operación de SC en interiores de la industria electrónica del noroeste de México

López-Badilla G.
Cybernetic and Electronic Department
Researcher and in Corrosion and Materials
CETYS, Mexicali, BC
E-mail: glopezbadilla@yahoo.com

Vega-Matus A.
Students of Cybernetic and Electronic Engineering
CETYS, Mexicali, BC
E-mail: av2311@hotmail.com

Millán-Arce D.
Students of Cybernetic and Electronic Engineering
CETYS, Mexicali, BC
E-mail: dm2010@hotmail.com

González-Kleyton J.
Students of Cybernetic and Electronic Engineering
CETYS, Mexicali, BC
E-mail: jgz1200@gmail.com

Contreras-León G.
Students of Cybernetic and Electronic Engineering
CETYS, Mexicali, BC
E-mail: gc5455@gmail.com

Abstract

The electronics industry is an important factor in Mexico’s economy, representing 80% of companies in the northwest of this country, where we find Mexicali (as arid zone) and Tijuana (as marine region), two cities in the state Baja California, adjacent to cities in California, USA, on the border of Mexico-United States. A study was conducted indoors in three plants of each city mentioned above, to determine if corrosion phenomena has an effect on the lifetime and productive performance of the CS. The results show that major air pollutants present indoors, that generate aggressive environments in Mexicali are the sulfides, while in Tijuana are the chlorides, which affect the functioning of the CS, and originate electrical failures in industrial equipments and machines.

Keywords:
• corrosion
• control systems
• climatic factors
• air pollutants
Introduction

The electronics industry is using electronic devices called control systems (CS), which are applied in the industrial plants; they are essential for improving the efficiency of manufacturing processes, and when its have malfunctions, the economy of any company has economic losses. The phenomenon of corrosion is presented by changes in climatic factors such as humidity and temperature, and the presence of air pollutants such as SO$_2$, H$_2$S, NO$_x$, and Cl$^-$ in Tijuana, which exceed the air quality standards set by SEMARNAT-México and EPA-EU, at certain times of year. This affects the operations of CS, with the consequence of electrical failures in equipment and machines of industrial plants. The lifetime of the CS evaluated were reduced by 25% in presence of corrosion and the quality of products manufactured in this zone of Mexico decreased by 30%. This represents economic losses to the companies in this region.

Atmospheric pollution

Gaseous and solid airborne pollutants comprise small dust particles of hydrogen sulfide (H$_2$S), sulfur dioxide (SO$_2$), chloride ions (Cl$^-$) and nitrogen oxides (NO$_x$), which are capable of penetrating into indoor areas of control systems (CS). This study shows some ways to control these parameters to keep away from the presence of corrosion and have efficient operation of CS to conserve with better conditions the lifetime of CS for a long time (Veleva et al., 2008; Dillon, 2000). The life time of the CS evaluated were reduced by 25% in presence of corrosion and the quality of products manufactured in this zone of Mexico decreased by 30%. This represents economic losses to the companies in this region. The generation of corrosion in electronic devices and equipment of automobiles has been important in recent years, when the complexity of electronic systems used in electronic equipments and machines is increased to improve their efficiency.
the industrial plants through inlets of air filtering systems. These pollutants generate aggressive indoor environments in combination with humidity and temperature, producing corrosion damage of metallic components of electronic equipment. In spite of the existing corrosion prevention and protection system as well as the application of electronic industry standards, corrosion control is not easy in specific climatic regions, especially in arid and marine regions (Robertson and Fenderson, 2005; King and Mamdani, 1977). Arid zones are typical, with RH ranging from 30% to 90% in summer with temperatures higher than 40°C and winter temperatures lower than 5°C. In marine environments, the RH is around 20% to 80% and temperatures during summer rise to 35°C and go down to 3°C in winter. These factors, promoted by anthropogenic and natural activities facilitate the corrosion of the copper components. The corrosion of copper specimens was evaluated by the gravimetric method; it was correlated with the minimum average and maximum RH and outdoor temperature values in different seasonal periods, which affect the indoor climate plants. The efficiency of the electrical behavior of copper components in electronic devices is a function of the amount of humidity and pollutants present in the indoor environment (Belanger, 1995). This concerns companies for the economic losses due to defective electronic products, since it promotes rapidly the corrosion process on connectors and electrical connections and thus causing electrical failures, malfunctioning in electronic equipment and in some cases stops the manufacturing line. This brings warm temperatures, causing deterioration in some metallic materials used in the electronic connectors and connections such as copper. All this decreases the quality of the articles manufactured in this region and generates economic losses (Bishop, 1997). When variations of humidity are very drastic, several variations of temperature occur and therefore the electronic equipments and devices suffer changes in their functionality. To measure humidity ranges, it is necessary to install sensors indoors of industrial plants to be in contact with the environments.

Climate factors vs electrical failures

Electronic equipment and machines of industrial plants consist of printed circuit boards, also called e-cards. The lifetime of these electronic components is related to the type of material, operation and exposition to environment. In some cases, the durability decreases by the exposition to air pollutants and climatic factors, mainly drastic variations of humidity and temperature (López, 2008; Veleva et al., 2008; King and Mamdani, 1977). Engineering design, wrong manufacturing methods and inadequate mechanical movements generate improper installations. E-cards are constituted by a lot of electronic devices and are installed according to their operation, with sections separated with insulators to avoid electrical connections between undesirable zones (analog or digital signals), power (high and low), speed (high and low) and types of printed boards. There are a variety of electronic components, which are classified according to wave (sine, triangular, square or linear).

CS operations

Control systems automate engineering processes (CSAEP) are based on many parameters and are called programmable automation controllers (PAC). These devices have some objectives with stable signals, are robust to avoid errors, and very efficient according to a predetermined criterion avoiding sudden and unrealistic behavior (Dorf and Bishop, 2005; Lewis and Yang, 1997). The CS are necessary to process, monitor, and acquire data, store and display information to be analyzed. The CS are classified by their behavior and monitoring the variations of parameters involved in the systems, to know these in a depth objective. CS must be simple and easy to understand the operation of electronic equipments and machines for industrial plants; their output signals are related with the input signals. Mean age of a CS used in the companies analyzed was less than ten years, but most electrical, electromechanical and electronic equipments and machines with age higher than ten years are not highly efficient and generate low levels of productivity. Sometimes it is necessary to use new industrial machinery to generate the adequate yielding (Kuo, 1995; Ogata, 2002; Phillips and Harbor, 2000; Goodwin et al., 2001).

The CS are composed by electronic analog components principally, that not are protected by package systems as integrated circuits (IC) and are exposed easily to indoor aggressive environments of the electronics industry. This causes, easy and rapidly, the corrosion process in their electrical connectors and connections (ECC). Figure 1a and 1b, show the manufacturing process and operation of the CS to detect products fabricated in the electronics industry of this region, to determine if articles manufactured are accepted or rejected and to find out if the companies have economic gain or losses. A process of insertion of electronic equipment in electronic boards (e-cards) controlled by CS in the production of television and a CS in steps are represented below.
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Electronics industry

The electronics industry has grown over the past fifty years, contributing to the economy. Particularly in the State of Baja California, these companies have prospered in the industrial parks of Mexicali and Tijuana. This type of companies is installed in the principal cities of Mexico, most notably in the border with the US, specifically in the northwest. At the beginning of the industrial activities in the electronics industry, the manufacturing process was used to control variables with manual operations and in later times, CS were designed and produced to improve the industrial process, and to obtain better yielding and reduce the errors. The use of CS was a change that revolutionized the industrial machinery and the research activities indoors of the electronics industry (Lopez et al., 2007, 2010; Cole and Paterson, 2004; Annual book ASTM, 2000; ASHRAE, 1999; Lopez et al., in press). In the 20th century, the use of these devices was very important for innovation, and in our times the goal to follow is to produce new CS at micro and nano scales, applied in aeronautic, biomedicine and spatial and telecommunications.

Industrial plants in Mexicali and Tijuana

In the electronics industry of Mexicali and Tijuana, there are a variety of devices and electronic equipment inside the plants which generate big quantities of products sold in areas around the country and the world. Three of four companies in this city produce or have electronic systems in their manufacturing process, belonging to the Assembly Plants Association (APA, 2010).

Cost vs productivity

Manufacturing plants work every day to reduce costs and increase productivity. CS cover the majority of requirements in the industrial process, replacing labor for CS, reducing the human error and costs (ISO, 1992, 2005, 2006). With the incorporation of this technology, control process in real time, development of complex strategies, production suggestion and important management decisions are the everyday life of the companies. In each implementation of CS, it’s necessary to evaluate costs and benefits, the financial support is applied in the areas with major economical retribution.

Adaptive control systems (ACS)

This system is capable to modify the behavior as a transformation of their signals altered by the functions or external disturbances as close loop system (CLS). Analysis with different equations and block diagrams shows the functions step by step, indicating the relation of the parts of the electronic equipments and machines (Quiang and Wen, 2006). In the five companies evaluated this type of CS are installed with feedback steps to adapt the changes generated by internal or external signals, with design by analysis (detecting and modifying the main characteristics) and by synthesis (evaluating the changes and generating news in real time).

Matlab software

MATLAB is a numerical computing environment and programming language, which was created by MathWorks and allows easy matrix manipulation, creation of graphs of functions and data, implementation of algorithms, creation of user interfaces between operations and other programs in different languages (Balachandran, 2005). One advantage of the use of CS with specialized software, such as MatLab, is being able to predict the performance of any industrial process and the operation of products manufactured. The data was evaluated using this software to determine in real time the industrial process and improve it for the future parameters of manufacturing operations. Linear regression analyses were performed to get the best fit models for experimental data and the trend of better yielding.
Experimental

Electronic equipments and machines of industrial plants controlled by small devices as control systems have better yielding. In this study, the use of CS and the probability to suggest in a short period of time the use in micro and nanotechnology, was analyzed (Zlatev et al., 2008; Sankara et al., 2007; Valdez and Schorr, 2006; Lopez et al., 2010).

Corrosion testing

Copper specimens for corrosion testing were exposed at indoor conditions of electronics plants for a period of two years in Mexicali and Tijuana. The specimens corrosion was evaluated according to the ASTM standards G 1, G 4, G 31 (Annual book of ASTM, 2000), and correlated with the minimum, average and maximum outdoor RH, TOW and temperature parameters (ISO, 1992). Also the Sulfatation Plate Technique (TPS) (ASTM, 2010) was applied in Mexicali, as well as TPS and the wet candle methods (WCM) (ASTM, 2008) in Tijuana; the electronic plants in Tijuana are located in industrial parks, while in Ensenada, plants are located at distances ranging from 1 km to 10 km from the sea shore. Rectangular specimens with dimensions of 2.5 cm x 1 cm x 0.5 cm were cleaned by immersion in an isopropyl alcohol ultrasound bath for 15 minutes. Immediately after cleaning the copper specimens, they were placed in sealed plastic bags, ready to be installed in the test indoor sites. After each exposure period the specimens were removed, cleaned and weighed to obtain the weight loss and to calculate the corrosion rates (ISO, 2005). The corrosion products morphology was examined with an optical microscope. The most active gases are hydrogen sulfide (H\textsubscript{2}S) and SO\textsubscript{x}. H\textsubscript{2}S is a corrosive and toxic pollutant which originates from municipal sewage (ISO, 2006).

CS age in electronics industry

Analysis of using time of electronics equipments and machinery in the electronics industry of this city was made in relation to their production yielding. The major industrial process evaluated showed efficient operations with the use of CS, increasing the quantity of products with less mistakes. This study indicates that use of obsolete electromechanical and electronic machinery with CS is a very productive systems and companies have opportunity to economically support the improvement of each equipment and machine (Lopez, 2008).

Mathematical simulation

A mathematical correlation was made in MatLab software (Duncan et al, 2005) to determine the corrosion levels (CL) indoors of electronics industry in Mexicali and Ensenada. With this analysis the deterioration grade (DG) of metallic probes of copper was found, correlating the climate factors (humidity and temperature), air pollutants (CO, NO\textsubscript{2}, O\textsubscript{3} and SO\textsubscript{2}) from outdoor sources that penetrate by inlets or air-conditioning systems to the interior of industrial plants, and corrosion rate (CR). Models were developed to simulate industrial processes with MatLab software. This represents the difference of using or not CS with signals indicating the levels of productivity and errors.

Microscopy analysis

Electrical connections and connectors of copper of CS were analyzed by Scanning Electron Microscopy (SEM) to determine the aggressive agents that react with the copper surface (Veleva et al., 2008; Lopez et al., 2010). For evaluation of the corrosion effect on the metals, weight loss measurements were performed. Following the weight loss determination, the corroded metallic specimens were subjected to chemical cleaning to remove the corrosion products from the surface, degreased with ethanol in an ultrasonic bath for 5 min and weighed. All results presented in this study are averages of triplicate specimens. The corroded specimens were analyzed by scanning electron microscopy coupled to an electron dispersive X-ray analyzer (SEM EDS, Phillips XL ESEM). X-ray diffraction (XRD) analysis of the corrosion products and their evolution in time was performed using Siemens D 5000 diffractometer with Cu K\alpha monochromatic radiation (Lopez, 2008; Lopez, et al., 2007).

Results and discussion

The control of industrial processes is fundamental in manufacturing operations to save economical funds and improve the electronic machinery used in industrial plants. This study shows an important relation that suggests companies of this region should install ACS in their industrial operations.

Operation analysis of CS

An analysis of productive yielding was made to find the differences of using new and old control systems. This information is shown in diverse evaluations as 1 to
5 (Table 1), 5 to 10 (Table 2) and more than 10 years (Table 3) of age of CS used in three functions, indicating the percentage in each operations. In Table 1 the productive yielding is higher than 80% in all activities and in the three companies in the cities evaluated, being to 1 to 5 years of CS age. This is because the ECC are not affected completely by the corrosion. In Table 2, the range of percentages is from 60% to 70%, with same characteristics of Table 1, of 5 to 10 years of age, indicating that ECC suffer a partial deterioration by corrosion, and Table 3 shows the percentages under 50% in all conditions mentioned above about the correlation of productive yielding and CS age, representing the full deterioration of ECC, after more than 10 years of operation.

Other factors analyzed were economic, technical and health parameters with old and new control systems, to determine the productive yielding related with the efficiency, costs, organization of industrial processes and technical support. The information in Table 4 represents better conditions to save costs with good efficiency, less consumption of electrical light and space occupied of CS as advantages; and less problematic situations of use new CS respect to technical operations for use of operations manual correctly and accidents occurred by ignorance of the operation of new control systems as disadvantages.

The Table 5, shows the same characteristics of Table 4, with the use of old control systems, indicating less efficiency, most consumption of electrical light and space occupied by CS, and more severe problematic situations with technical operations without operations manual, and this originated manufacturing processes unsafe, which generated more accidents in workers.
MatLab simulation

Numerical analysis was made to determine the correlation of the average of fabricated products of three industrial plants in both cities mentioned above, and the ranges of humidity and temperature at indoor conditions in the electronics industry. Figure 2 shows the minimum productivity with values of RH from 15% to 45% and temperatures less than 10°C, while the maximum productive yielding was in values of RH higher of 80% with temperatures from 20°C. Figure 3 shows too the minimum productivity with values of RH from 30% to 60% and temperatures higher to 15°C, and the maximum productive yielding was in values of RH near to 90% with temperatures less than 20°C. At low RH and temperature values, is formed a invisible thin film of water and occur the electrochemical process in some areas of ECC, and the corrosion rate (CR) was low, generating pitting corrosion, and at high RH and temperature ranges, the corrosion was high and, occurring uniform corrosion and deteriorate rapidly the ECC. The mathematical equation which evaluated the climate factors and air pollutants that increase the corrosion rate, is described as:

\[
f(x) = \frac{2}{3}x^3 - \frac{1}{2}x^2 + \frac{3}{5}x - \frac{5}{6}
\]
Influence of climate factors and air pollutants on CR

The values of RH and temperature were higher than 70% and 35°C during the year in Mexicali and with a minimum of 20% and 30°C in the periods of hot desert winds (early winter and spring) and maximum of 80% and 10°C in the rest of the year in the Tijuana area. High levels of humidity and elevated temperature accelerated the rate of corrosion. In summer the corrosion rate was higher after six months in Mexicali and for this reason the evaluation was also made for six months in Tijuana. For temperatures in the range from 25°C to 35°C, and RH level of 30% to 70%, the corrosion rate was very high. Furthermore, in winter, at temperatures around 15°C to 25°C and RH levels from 35% to 75%, water condensates on the metal surface and the copper corrosion rates increased very fast. Variations of relative humidity in the range from 30% to 80% and temperatures from 0°C to 35°C, and concentrations of air pollutants such as sulfides in arid zones and chloride in marine environments, exceeding the permitted levels for air quality standards, are also an important condition that favors corrosion. Table 6 shows the correlation between copper and the air pollutants; SO₂, NOₓ, and O₃, the principal climate factors (RH and temperature), concentration level of pollution and the corrosion rate (CR) at Mexicali city conditions, as a simulation in MatLab. SO₂ was the air pollutant with major corrosion effect; in the winter season. The CR arises the highest value (283 mg/m² year) when the RH, temperature and the concentration of sulfur dioxide values are 84.2%, 28.2°C and 0.52 ppm, respectively.

<table>
<thead>
<tr>
<th>Climate factors</th>
<th>Sulphur dioxide (SO₂)</th>
<th>Nitrogen oxides (NOₓ)</th>
<th>Ozone (O₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RH a</td>
<td>T b</td>
<td>C c</td>
</tr>
<tr>
<td>Spring</td>
<td>Max 67.6</td>
<td>38.3</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Min 26.7</td>
<td>16.4</td>
<td>0.07</td>
</tr>
<tr>
<td>Summer</td>
<td>Max 89.4</td>
<td>41.5</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Min 39.3</td>
<td>23.6</td>
<td>0.10</td>
</tr>
<tr>
<td>Winter</td>
<td>Max 84.2</td>
<td>28.2</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Min 28.4</td>
<td>19.7</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*RH. Relative Humidity (%), *T. Temperature (°C), *C. Concentration Level of Air Pollutant (ppm), *CR. Corrosion rate (mg/m² year)
Microscopy examination

SEM analyses were carried out to determine the corrosion products formed in the copper surface. Figure 4a shows scanning electron micrograph (SEM) in Mexicali, and Figure 4b in Tijuana; images of areas selected covered by the principal corrosion products which are rich in chlorides for Tijuana test results and sulfides for the Mexicali specimens. The SEM analysis of Cu specimens was generated, it shows an analysis of the chemical composition of the thin films formed in the Cu specimens installed in industrial plants in both cities the surface analysis is shown. These air pollutants generate aggressive environments indoors of the electronics industry and react with ECC. In contrast to outdoor exposure, in an indoor environment the wet film on the metal surface is thinner and it is often governed by relatively constant controlled humidity conditions. Sometimes the indoor environment temperature and RH are controlled and as a consequence, the amount of adsorbed water on surfaces is minimal and is constrained within reasonably tight limits.

AES examination

AES analyses were carried out to determine the corrosion products formed in the CS installed in the electronics industry of Mexicali and Tijuana. The Auger spectra of ECC was generated using a 5keV electron beam, which shows an analysis of the chemical composition of thin films formed in the ECC of CS (Figure 5). The AES spectrum shows the surface analysis of three points which represents the different zones of ECC. The peaks of steel appear between 180 eV, finding the sulfides. The chemical composition in the both analysis was revealed, with different concentrations of chloride, sulfur, carbon, nitrogen, oxygen, which damage the copper surface.
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In the analysis of Auger spectra in Tijuana that is a marine environment, the major air pollutant that reacts with copper surface was the sulphur, that occured in Mexicali. Auger spectra indicate the air pollutants combined with CO2 of the environment. Table 7 represents the atomic concentration of metallic probes with the percentages of air pollutants and carbon and oxygen.

Other analysis were made to determine by periods of time the damage of the presence of tarnishing or corrosion products in ECC, and depending if the operation efficiency of CS is known, as showed in Table 8, with more presence of the corrosion phenomena when the CS was used more time.

Conclusions

The miniaturization and the requirement for high component density of small electronic devices need closer spacing and thinner metallic paths affected by corrosion and electrical failures. Copper exposed to air pollutants reveal that an increase on their concentrations at outdoor conditions has a critical impact on the indoor corrosion process in arid and marine environments. RH values higher than 75% and concentration of air pollutants, promotes corrosion. New technology with CS used to improve the manufacturing process of the electronics industry in the northwest of Mexico, is an important factor to increase their productive yielding.

The CS are affected by aggressive environments principally sulfurs in Mexicali and chlorides in Tijuana, and decrease their operative efficiency. This study shows the necessity to replace constantly the CS in industrial plans of this region to avoid economical losses. Pitting corrosion was present in winter in both cities and uniform corrosion in summer. The control of the microclimate indoors of the electronics industry is necessary and the constant check of the operative efficiency of CS, to maintain manufacturing processes with excellent conditions.

Discussions

Corrosion in electronic systems of cars was increased in the last 30 years. In this process galvanic electrochemical cells are formed, which are capable of generating electrical failures. Copper is used in electronic devices and equipments for the manufacturing of electrical connections and connectors, for its good electrical and thermal conductivity.

Microcircuits, electrical connectors and connections of copper are very susceptible to the atmospheric corrosion in both cities mentioned above. Scientists in corrosion and materials consider that a bad operation of electronic systems of cars is due to the presence of corrosion in their unions.

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About the authors

Gustavo López-Badilla. Was born in Santa Ana, Sonora, in the northwestern of Mexico, he is an Electronics Engineer, MI Systems Engineering, Doctor in Industrial Chemistry and is a Postdoctoral in Physical Chemistry and Surface Analysis (Nanoscience and Nanotechnology Center-UNAM) candidate. He is a member of the National System of Researchers (SNI) in Mexico. Has six years experience in industry and 11 years in Research and Teaching in the basic areas of Mathematics, Physics and Chemistry. Assistance to 20 national and international conferences and 35 extension publications: technical and scientific, in electronic, corrosion, materials, environment and surface analysis and participate in two books. He has won a national award in Materials Congress.

Ángel Vega-Matus. Student of 8th semester of Cybernetic and Electronic Engineering, with two years of experience in industrial plants.

Diego Millán-Arce. Student of 8th semester of Cybernetic and Electronic Engineering, with two years of experience in industrial plants.

José González-Kleyton. Student of 8th semester of Cybernetic and Electronic Engineering, with three years of experience in industrial plants.

Guillermo Contreras-León. Student of 8th semester of Cybernetic and Electronic Engineering, with one year of experience in industrial plants.