Corrosion Studies on Stainless Steel 316 and their Prevention – A Review

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Abstract: *Corrosion is a process that causes a change of metal to chemically stabled form, by reacting with a solution or with the atmospheric air. There are various types of corrosions such as crevice corrosion, intergranular corrosion, stress corrosion, pitting corrosion, galvanic corrosion and uniform corrosion. These types of corrosion and the prevention methods are investigated in this review paper. Stainless steel 316 has excellence in corrosion resistance, due to the presence of molybdenum content. From the literature survey, stainless steel 316 has been tested in various experiments to improve the properties of the material. In the present review, several coating processes and additives which are added on SS 316 to improve the material properties are studied. The advantages of these improvements are reduced cost of change of material, reduced loss of material due to corrosion and increase in materials durability. Hence, stainless steel 316 is used for all corrosion applications which causes less damage and high durability compared with other austenitic steels.*

Key Words: *electrochemical corrosion, stainless steel 316, corrosion resistance*

1. INTRODUCTION

Corrosion is noticed in some material which is covered with orange or reddish-brown colored layer. It is a process in which the refined metal is converted to more stable compound such as metal sulfides, metal oxide or metal hydroxides.

The iron involves in rusting due to the formation of oxides through atmospheric moisture and oxygen. This kind of rusted materials becomes brittle, and flaky. Corrosion is also described as an electrochemical process which involves chemical reactions between the metal and certain atmospheric agents such as moisture and oxygen. The factors that affect corrosion are:

- ✓ Experience of the metal to a gas containing like CO_2, SO_2, etc,
- ✓ Experience of the metal to moisture on saltwater,
- ✓ Existence of acid in the atmosphere which increases the process of corrosion,
- ✓ Increasing the corrosion rate by increasing the temperature.
- ✓ Presence of impurities (NaCl)

There are some types of corrosion which cause serious damage to the material like crevice corrosion, intergranular corrosion, stress corrosion, pitting corrosion, galvanic corrosion and uniform corrosion.

The crevice corrosion is the dissimilarity in ionic concentration between two local areas of any metal which leads to corrosion. It occurs in gaskets, bolt heads, and under the surface of washers etc. Most of the aluminum alloys and stainless steel undergoes crevice corrosion. Stress corrosion is a metal cracking phenomenon which is the result of the corrosion environment. It often occurs due to high temperature. A good example is the austenite stainless steel in chloride solution in which stress corrosion cracking occurs. The impurities present in grain boundaries separate the grain during solidification on metal which occurs in the intergranular corrosion. It also occurs in the enrichment of alloy at boundary conditions, for example, in case of all aluminum - based alloys which can be affected by intergranular corrosion.

Galvanic corrosion occurs when there is an electric contact between two materials in an electrolytic environment. The process of degrading occurs in a salt water environment or copper in contact with steel. The Pitting corrosion occurs in the formation of corrosion cell by the metal surface. It is unpredictable to detect. Once this ‘pit’ is formed, it grows continuously with various shapes. The uniform corrosion is the common form of corrosion, which is formed in the surface of the metal when interacting with the atmosphere. It causes a low impact on the materials and it spreads over the whole material uniformly [1].

2. EXPERIMENTAL STUDIES

Stainless steel 316 weld metal with 0.07% nitrogen was subjected to manual metal arc (MMA) welding process.

The pitting corrosion was evaluated in both welding and aging conditions. The evaluation on microstructural studies in aged conditions was performed at 1023 and 1123 K for 0.5, 1, 10, 100h.

In these studies, electrochemical potentio-kinetic has no reaction peak due to the absence of Cr depleted zone. Hence the pitting corrosion resists the sigma, carbide and Cr_2N phases in the weld metal which was aged for 100 h at 1123K [2].

In stainless steel 316, microstructure and corrosion performance were analyzed by laser melting deposition (LMD). During LMD, the ring-shaped beam produces small residual stress that avoids sintering, the heat accumulation, and improves the surface coating quality. The performance of electrochemical corrosion of stainless steel 316 coatings with various processing parameters was studied. The result showed that the stainless steel 316 has enhanced corrosion resistance performance which was 30% overlap ratio comparing with stainless steel 304 substrate [3].

The intergranular cracks and grain boundary network on stainless steel 316 have been experimented in stress corrosion cracking.

The large grain-clusters play a vital role in grain boundary engineering improvement [4]. Thioacetate hexadecyltrimethoxysilane was deposited on SiO_2 coated with SS316 to form a thioacetate-functionalized monolayer.

TiO_2 solution was covered on the surface of stainless steel 316 with a metal layer of 5-10 nm. Thus, the cyclic voltammetry and potentiostatic current demonstrated the efficiency of corrosion protection which acts against the pitting corrosion [5].

On laser surface melted stainless steel 316, the localized corrosion studies were performed. The stainless steel 316 which is solution annealed is cold worked (5, 10, 15 and 20%) and sensitized (923K, 20 h). Using scanning electron microscopy, X-ray diffraction and optical microscopy, the characterization was performed on the melted layers of stainless steel 316. For the pitting corrosion studies, the solution annealed specimens were carried out by the potentiodynamic polarization method on the melted region. The result explains that the laser surface melted can be used as an in-situ method to enhance the durability by modifying the surface microstructure and also enhancing localized corrosion resistance [6].

Electrochemical Noise technique is used to investigate the pitting corrosion behaviour of the stainless steel 316. Electrochemical corrosion behaviour of SS316 in a deaerated solution of sodium chloride and sulfate was analyzed. The result showed the enhanced pitting corrosion resistance on the stainless steel 316 by using the electrochemical noise technique [7]. Stress corrosion cracking growth on SS316 in solution-annealed and sensitized (at 923K for 20 h) conditions was studied. The test was conducted in an environment of boiling 5 M NaCl + 0.15 M Na_2SO_4 + 2.5 ml/ HCl using the fracture mechanism approach. By stress parameters, the crack growth rates were calculated. The high plateau crack growth rates were found on sensitized stainless steel (solution – annealed material) [8].

The investigation of the corrosion behaviour on stainless steel 316 with Ni-Cr-Mo laser coating and X70 steel with H_2S and CO_2 solutions was performed. This application was concentrated on oil industries on coating applications, its surface morphology and corrosion behaviour on CO_2, H_2S separate solutions as well as mixed gas were studied and compared with stainless steel 316 and X70 steel. The results show that 316 SS and X70 displays inclusions on the surface before corrosion, while Ni-Cr-Mo coating exhibits higher corrosion resistance. From each simulated solution, this coating enhances corrosion resistance as compared to pure SS316 and X70 steel. It also has an elevated polarization resistance as compared to 316 SS and X70 steel [9].

The erosion in the corrosive environment has been identified in chemical and hydrocarbon extraction industries which accelerate the material loss and the surface wear. The surface morphology of SS316 (both erosion and erosion-corrosion environment) was analyzed using focused ion beam and transmission electron microscopy techniques. In 1% uncrushed silica and 7 m/s velocity, the samples were placed for 60 min and tested. The result is reducing in work hardening behaviour and high erosion-corrosion rates were identified [10].

In material development, with high temperature fluoride salt cooled reactor, the corrosion tests of SS316 were performed in primary coolant, molten Li_2BeF_4 at 700˚C for 3000h long duration. This test was performed in both graphite capsules and stainless steel 316. From the corrosion test, the corrosion attack depth in Li_2BeF_4 salt was predicted as 17.1 µm/year and 31.2 µm/year for stainless steel 316, respectively [11]. Table 1 shows the outcomes of the experimental studies investigated by various researchers.

3. PREVENTION

To avoid the huge losses of the material, the prevention of corrosion is necessary. This involves many applications in areas such as in automobiles, machinery, household goods, railway lines, bridges etc. The metal is coated with a thin layer on the electrochemical process of another metal using electrolysis. Copper or nickel is selected as anode, and cathode act as sacrificial metal which corrodes other metal instead of base metal. By this method, the electrons ejected and get oxidized.

Thus, ions formed in the corrosion process by saving the base material. Painting and greasing provide a layer on the material to prevent the exposure of material corrosion with the external environment.

By choosing a material to increase the corrosion resistance, the presence of molybdenum element should be high on the material.

This presence of molybdenum content decreases the corrosion rate comparing other alloys or materials. By using corrosion inhibitors, the chemicals are added to the corrosion environment which can cut down the rate of corrosion [12].

Table 1 – Corrosion behavior study on stainless steel 316

Author	Experiments	Outcomes	Data/Solution
Loto et. al., [13]	In the polarization test, sulphuric acid and phosphoric acid with stainless steel are done. A similar test with NaCl (2% addition, 20g/l) is performed in specified acid concentration	Besides, 2% NaCl test concentration has increased in active corrosion reaction. This shows the enhance in the corrosion resistance on SS 316	In H_2SO_4, medium concentration (9.1 M; 48.5%), high concentration (18.2 M; 97%), and absolute passivity. (18.2 M). It is same in H_3PO_4 (7.4 M; 42.5% and 14.8 M; 85%)
Li et al., [14]	In SS 316, PEMFE with dilute HCl and 80˚C hydrogen gas is investigated. Both polarization curve and EIS measurements are done.	The corrosion behaviour of SS316 in both dilute HCl and SO_4^{2-} are similar and shows an inhibitive effect. Thus coating is necessary for enhancing the corrosion resistance	In 0.01 M HCl solution and In 0.01 M HCl + 0.01 M Na_2SO_4 solution
Loto et. al., [15]	Electrochemical noise generation technique, testing on acidic chloride environment	The corrosion behaviors are related to pitting/general corrosion mechanism through SEM	Investigated in 3.5% NaCl solution
Yi et. al., [16]	Potentiometric polarization behaviour was investigated based on the scan rate effect	SS316 with NaCl solutions result showed that the scan rate is highly influential on critical pitting potential. The parameters in pitting resistance on the material were determined.	Polarization curves are measured in 3.5% NaCl solution at scan rates from 0.01 to 50 mV/s
Anwar Ul-Hamid et. al., [17]	Experiments were exposed to seawater and splash conditions were done to find the corrosion properties	The material was analyzed for 15-months. SS316 had excellent corrosion resistance when compared to SS 304	At splash zone condition – SS316 has 0.86 µm/y and stainless steel 304 has 1.13 µm/y

Several factors cause stainless steel 316 to corrode and the following methods describe the causes and prevention. The presence of sodium chloride (NaCl) can cause pitting corrosion. The pitting corrosion is exposed to environments that have the presence of enormous salt (Chloride). If stainless steel 316 is used for marine applications, it may cause pitting due to direct contact with seawater (sea-enriched).

To avoid pitting corrosion, the specialized coating can be applied to stainless steel 316 (by avoiding direct contact with chlorides). Galvanic corrosion is formed when welding dissimilar stainless-steel.

The less noble metal which accepts new electrons quickly will become an anode and start to corrode (corrosion takes place rapidly). The best method to prevent bimetallic corrosion is to avoid joining two dissimilar metals permanently. Coating the metal shall prevent the flow of electrons from the cathode to the anode.

Transplanting of plain iron or steel onto stainless steel in some applications causes corrosion. For example, an iron piece is transferred onto the surface of a stainless-steel part or basket. These particles can disrupt the protective oxide layer of the stainless-steel workpiece and rust forms.

To prevent the transplanting of plain steel or iron to stainless steel workpieces, it's necessary to thoroughly clean and prepare equipment when changing over to new material [18]. The effect of low-temperature oxy-nitriding (LTON) treatment, the liquid lead-bismuth eutectic (LBE) corrosion behaviours on stainless-steel 316 were studied under the vacuum at 823K in the stagnant liquid LBE.

The result shows that the untreated samples were severely selective leaching in liquid LBE contact. LTON treatment produced an outer porous Fe-Cr spinel film and inner S phase layer on the surface of the sample, which transformed into a thicker spinel film containing γ low-N and region distribution with CrN precipitate after liquid LBE corrosion.

The main attribute is the oxidation and decomposition of the S phase in a metastable phase and easier to be oxidized than matrix in high temperatures. It showed an improvement in the ability to form protective oxide film for materials [19].

The investigation on the decrease in pitting corrosion resistance of extra-high purity type stainless steel 316 with Cu 2+ in NaCl was performed.

The effect of Cu 2+ in bulk solution on pitting corrosion resistance of extra-high purity type stainless steel 316 was done. Pitting occurred in 0.1 M NaCl-1 mM $CuCl_2$, whereas pitting was not initiated in 0.1 M NaCl.

The deposition of Cu 2+ on the surface occurred regardless of a potential region in 0.1 M NaCl-1 mM $CuCl_2$, Cu 2+ in bulk solution which did not influence passive film formation. The decrease in pitting corrosion resistance in 0.1 M NaCl-1 mM $CuCl_2$ resulted in Cu compound deposited and supply of Cu 2+ on the surface [20].

Additively manufactured stainless steel receives widespread attention due to its excellent mechanical properties, corrosion mechanism in Cl--. Researchers reported the pitting and passivation behaviour of additively manufactured stainless steel 316 in 3.5 wt.% NaCl solution.

The result shows that stainless steel 316 exhibits a fine sub-grain structure of 5 μm in diameter and dislocations and Mo elements enriched at the sub-grain boundary. Compared with the wrought 316L stainless steel, huge sub-grain boundaries and high dislocation density promote the formation of the more compact and thicker passive film. The low hydroxide content in the passive film and the micro-galvanic corrosion effect between Mo-rich sub-grain boundaries and sub-grains reduce the self-repairing ability of passive film. Hence, the pitting corrosion resistance of stainless steel 316 is higher [21].

4. FUTURE SCOPE

The stainless steel 316 is an excellent material to reduce the corrosion rate and it is widely used in all corrosion applications. To increase the durability of the material, the method of additive or coating with selective materials can be further applied to increase the corrosion resistance with experimental tests.

5. CONCLUSIONS

In this paper experimental studies were performed on 316 stainless steel and several classifications of corrosion studies as well as corrosion prevention were investigated. The prevention of these types of corrosion can be achieved through electroplating, cathode protection, galvanization, painting and greasing, choosing the perfect material which has high corrosion resistance and using corrosion inhibitor. Hence, stainless steel 316 has excellent corrosion resistance, high durability, mechanical strength compared with other austenitic stainless steel. The properties are further improved by adding additives and performing coating process on the stainless steel 316.

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