Effect of Dilution on Electrochemical Properties of Stainless Steel Clad Layer Using Submerged Arc Welding Technique

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تأثير التخفيف على الخواص الكهروكيميائية لطبقة الفولاذ المقاوم للصدأ باستخدام تقنية اللحام بالقوس المغمور

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Abstract:

This study investigated the effect of dilution on clad layers of stainless-steel type 316L deposited via submerged arc welding technique. Metallographic and corrosion testing methods were used to examine the dilution effect. Metallographic analysis showed that the interface between the substrate and SS316L layer was more susceptible to pitting corrosion compared to the top surface layer. Corrosion tests results - including weight loss and electrochemical tests- were consistent. In electrochemical testing, the top surface of clad layers exhibited better corrosion behavior as the passivity region started at a lower potential and lasted longer, indicating superior corrosion resistance. Weight loss test results also confirmed that the top surface of the clad layer provided enhanced corrosion resistance. The corrosion seen in top clad layers due to dilution was within acceptable criteria for engineering applications in seawater.

Keywords: Dilution, Stainless Steel Clad, Electrochemical Properties, SAW.

الملخص

تناولت هذه الدراسة تأثير التخفيف على طبقات كسوة الفولاذ المقاوم للصدأ من النوع L316 المترسب عبر تقنية اللحام بالقوس المغمور. تم استخدام طرق الاختبار المعدني والتآكل لفحص تأثير التخفيف. أظهر التحليل المعدني أن الموضع بين المعدن الأساس وطبقة SS316L كانت أكثر عرضة للتآكل النقطي مقارنة بطبقة السطح العلوي. نتائج اختبارات التآكل بما في ذلك فقدان الوزن والاختبارات الكهروكيميائية كانت منطابقة. في الاختبار الكهروكيميائي أظهر السطح العلوي للطبقات المكسوة سلوك تآكل أفضل حيث بدأت منطقة الخمول بجهد أقل واستمرت لفترة أطول، مما يشير إلى مقاومة تآكل فائقة. أكدت نتائج اختبار فقدان الوزن أيضًا أن السطح العلوي للطبقة المكسوة له مقاومة أكبر للتآكل. أثبتت الأختبارات أن التآكل الذي شوهد في الطبقات المكسوة العلوية بسبب التخفيف ضمن المعايير المقبولة للتطبيقات الهندسية في مياه البحر.

الكلمات المفتاحية: التخفيف، طبقة المعدن غير قابل للصدأ، الخواص الكهروكيميائية، لحام القوس المغمور.

Introduction

The performance of stainless-steel clad layers, especially in demanding environments, depend on their electrochemical properties, which are significantly influenced by the degree of dilution during the welding process. Dilution, the mixing of the base material with the clad layer material, notably impacts the microstructure, corrosion resistance, and thermal conductivity of the clad layers, affecting their suitability for various applications. Dilution alters the balance of phases within the microstructure[1]. it directly influences the

material's mechanical and corrosion behaviours such that lower dilution levels (22.57%) yielded a favourable microstructure with enhanced ductility and corrosion resistance[2]. Similarly, the extent of dilution dictates the clad layer's susceptibility to pitting corrosion due to compositional changes underscoring the importance of controlled dilution for achieving optimal corrosion resistance[3]. Furthermore, dilution has been linked to thermal conductivity (Sowrirajan et al., 2018), a critical property in thermal applications[4]. This introduction will explore the effects of dilution on these key properties, emphasizing the importance of precise control during welding processes like submerged arc welding (SAW) to achieve desired performance characteristics while avoiding the potential negative impacts of excessive dilution on mechanical integrity and corrosion resistance.This research addresses the critical challenge of maintaining the corrosion resistance of stainless steel cladding, commonly used in marine and industrial applications, after welding-induced thermal cycling and subsequent microstructural changes influenced by dilution.

Literature review:
Researchers focused on modelling and optimizing the SAW parameters to improve the product properties. Studies modeled the impact of weld dilution on hardness and residual stress in multipass gas tungsten arc and submerged arc welding of low alloy steel (SA508). Higher dilution increased weld metal hardness and reduced tensile residual stress. While dilution didn't affect base metal hardness near the weld, it did influence overall residual stresses due to stress interactions between weld and base metal. [5]. Some researchers investigated applying Taguchi method and non-conventional techniques, GA and PSO computing techniques to find optimal set of welding process variables that produce the desired weld bead width in submerged arc weld of mild steel. [6]. This study used the validity of Taguchi method to optimize submerged arc welding (SAW) parameters for improved mechanical properties (UTS and hardness) of A24 SS316 steel. The study demonstrates the value of the Taguchi method for optimizing SAW parameters and enhancing weld quality [7].
A study compared submerged arc welding (SAW), metal active gas (MAG) welding, and plasma arc welding (PAW) for joining ASTM A131 Grade A steel. All methods achieved good tensile strength, with fractures occurring near the base metal. PAW produced the highest hardness.[8].
Researchers examined the impact of dilution on microstructure in 3-pass GTA and SA welds of SA508 steel using different filler materials. Both processes produced martensite and bainite in the HAZ, while acicular ferrite dominated the SA weld and was mixed with martensite and bainite in the GTA weld. [9].
Some researchers focused on recycling submerged arc welding slag generated during stainless steel cladding. Cladding produced using recycled slag met ASME specifications for chemical composition and showed corrosion resistance, bend test performance, microstructure, microhardness, and ferrite content comparable to cladding made with fresh flux. Importantly, the recycled slag cost 73% less than fresh flux.[10]. Studies investigated the use of recycled submerged arc welding (SAW) slag as flux for stainless steel cladding, focusing on bead geometry, dilution, and microstructure. Results showed that welding current positively influenced penetration, bead width, reinforcement, and dilution, while travel speed negatively affected penetration, width, and reinforcement, but increased dilution. Increased voltage widened the bead and increased dilution but reduced reinforcement. [11].

Material and methods
Low carbon steel plates were cut to size 20 x 25 cm and used as a substrate to be cladded. The plates were degreased cleaned and grinded to prevent any contaminants that interfere and change the molten pool properties. The submerged arc welding machine type (ESAB LAF 1000 DC) used.
The parameters were set to achieve the best result. Table 1 shows the welding parameters.

Table 1: submerged arc welding parameters used in cladding SS 316L layers.

Amperage A	Voltage V	Speed m/min
380	28	1.5

The electrode wire was stainless steel 316L with a 2.4diameter. The flux used was agglomerated and made according to the old French standard NF A81.319 and contained chrome and nickel elements.
Two and three layers of stainless steel 316 L were deposited. The samples of two layers have thickness 3mm and the other samples of three layers have thickness 5mm. these different thicknesses were conducted as a strategy to determine the effect of dilution near the substrate-deposited layers interface and the dilution at the furthest point from the substrate surface.
To investigate the stainless steel layers, the layers were milled 1 mm deep through the deposited layers to make sure that all the machined layers are 100 % stainless steel.
The stainless steel deposits were then cut off into small pieces 10 mm x 10 mm. The samples were grinded and all the sharp edges were rounded and all scratches were eliminated to prevent any possibility of preferential corrosion.

Three types of corrosion tests were carried out to examine the effect of dilution on the electrochemical properties of the stainless-steel deposited layers.

1) Corrosion Metallography
Samples of different sides at the interface and at the top surface were investigated under a microscope before and after the experiment to check the changes in the surface attacked by the forced current in the corrosive 4.5% aqueous media. The pitting corrosion was magnified, filmed and compared to each other to determine the effect of dilution.

2) Weight loss test
Prepared samples (SS 316-2L represent samples of 2 layers while SS316-3L represents samples of 3 layers) were immersed in a solution of 4.5% sodium chloride NaCl for time periods (72, 160, 350,600) hrs.

3) Electrochemical Test
Gamry device was used to determine the electrochemical behaviour of the SS316L deposited layers in 4.5 % Na Cl at room temperature. The potentiodynamic mode was used to. First, the open circuit potential (OCP) was measured in 10 minutes running till the potential stabilised for satisfied period. Then the experiment was set to start at 200 mv lower (more anodically) than the OCP for all samples.

Results and discussion

1) *Corrosion products analysis*
The chemical analysis of the corrosion products at the top surface samples and the substrate-SS 316L deposited layer interface was carried out to determine the quantity of iron. This method can indicate how much the dilution is at the nearest and furthest points away from the substrate and the change in the chemical composition of the SS 316L deposited layers.

Below is the result of the chemical composition analysis.

Table 2: Chemical Analysis to Determine The Amount Of Iron In Corrosion Products.

Amount of iron as corrosion product in solution of Na Cl	
Fe quantity at top surface layer sample	1.15 ppm (mg/ L)
Fe quantity at interface layer sample the Fe amount	4.5 ppm (mg/L)

The amount of iron as corrosion products at the top surface of three deposited layers is lower than that at the substrate – SS 316L deposited layer by three times approximately. This shows some indication about the change in chemical composition between the different deposited layers in the same sample due to the dilution effect.
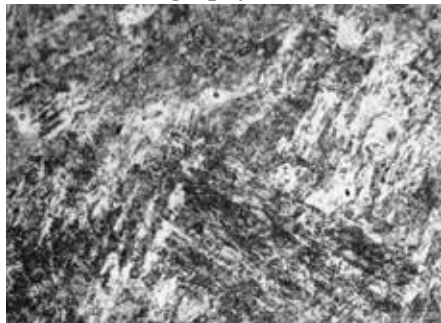
Corrosion Metallography

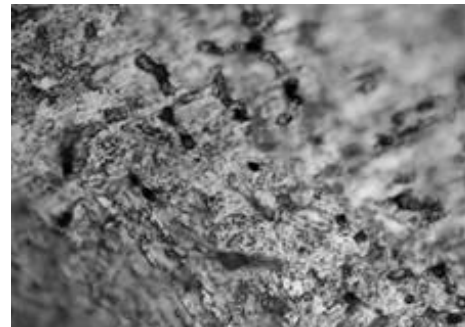**Figure 1:** substrate – SS Interface 1000x
before immersion

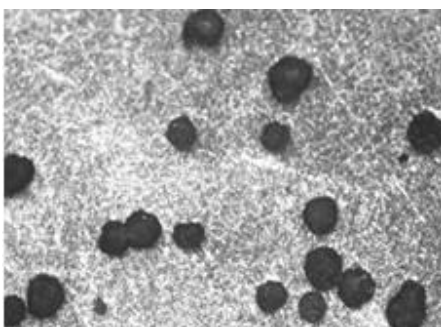**Figure 2:** Top surface 3L 1000x
before immersion

Figure 3: pitting corrosion at
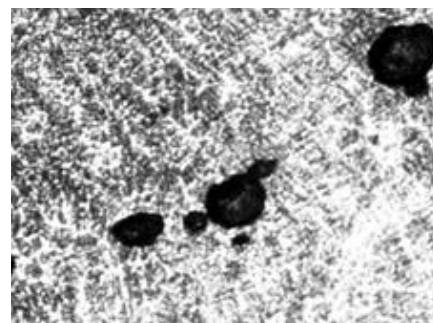Interface after immersion (400 x)

Figure 4: pitting at top surface 3L
after immersion (400 x)

2) Weight loss test results

The corrosion rates in mmpy units for both samples in various exposure times are shown in table (3).

Table 3: corrosion rate of both samples for different durations.

| Sample	Exposure Time(hr)	Wt.1 (gr)	Wt.2 (gr)	Wt.1-Wt.2 (gr)	Wt.1-Wt.2 (mg)	Area of 2 SIDES cm2	Corrosion Rate(mmpy)
SS 316-2L	72	5.232	5.2319	1E-04	0.1	6.2	0.002452957
SS 316-2L	160	4.505	4.501	0.004	4	6.2	0.048720801
SS 316-2L	350	4.979	4.975	0.004	4	5.1	0.032408435
SS 316-2L	600	5.197	5.193	0.004	4	6.2	0.019354839
SS 316-3L	72	4.953	4.9529	0.0001	0.1	6.72	0.002263145
SS 316-3L	160	5.791	5.79	0.001	1	6.34	0.011911237
SS 316-3L	350	6.239	6.237	0.002	2	6.34	0.013034938
SS 316-3L	600	5.821	5.82	0.001	1	5.26	0.005703422
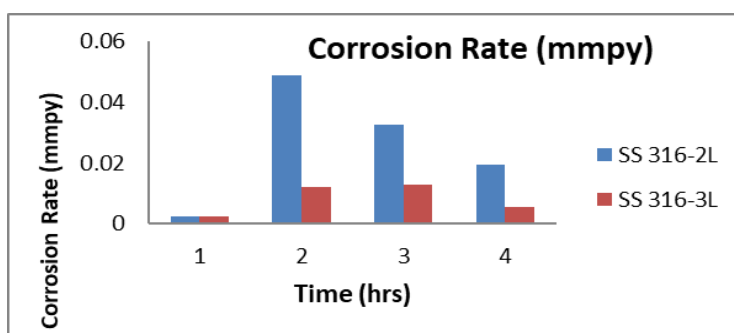
Figure 5: shows the corrosion rate of both SS 316- 2L and SS316- 3L for the immersion test.

The corrosion rate of SS 316-3L is less than that of SS 316-2L layer. According to the table 5 which shows the corrosion rate for 4 different periods, the corrosion rate of both deposited samples is very low with some superiority for the three layers samples. This is another indication implies the effect of dilution on the corrosion resistance of the deposited 316 stainless steel. Knowing that service behaviour is satisfactory when the average corrosion rate does not exceed 5 microns/48 hr. both SS 316-3L and 316-2L meet and satisfy the engineering applications criteria.

Electrochemical Test Results

Two samples were electrochemically investigated. One of the samples was taken from the top surface of three layer and the other faces of the sample were isolated and covered. The other sample was taken from the substrate- SS 316L interface and the other sides were covered to prevent any contact intervention. Both samples were anodically polarised starting with 100mv below the open-circuit potential for 20 minutes.
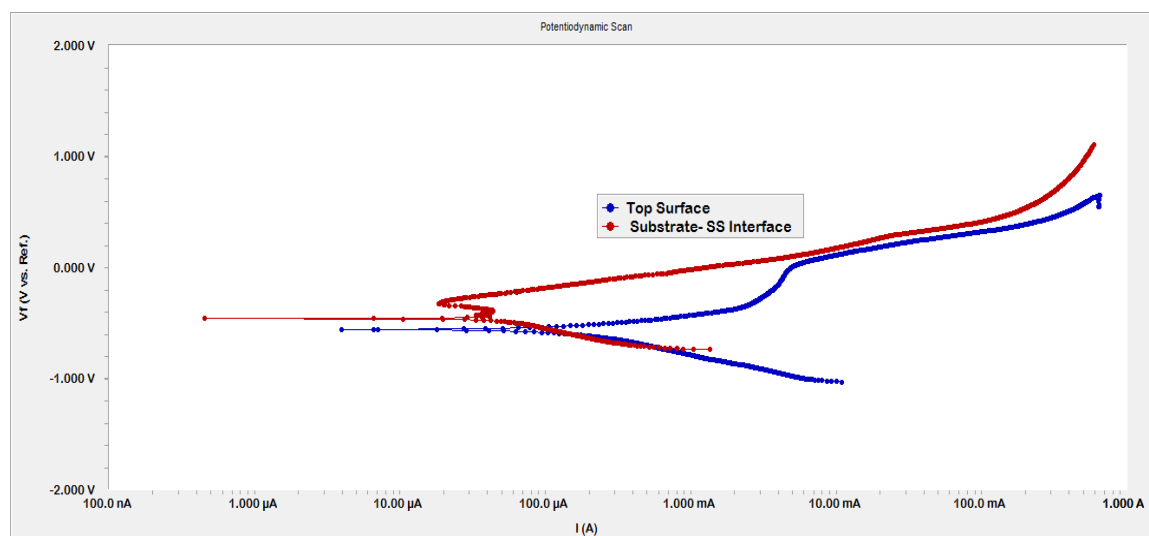

Figure 6: Comparison between the anodic polarization behaviors of the substrate – SS Interface and Top surface of 3-L sample in near-neutral, open to air, RT, 4.5 % NaCl solutions

The potentiostat instrument setup was such that to take the open circuit potential (OCP) of both layers in 20 minutes at 17 C, and started the measurement 500 mv more negative to polarise the samples anodically at a sweep rate of 0.001V/Sec. top surface of 3-L layer showed more negative OCP than substrate – SS Interface. When the applied potential to substrate – SS Interface increased toward more positive value oxidation was dominant reaction till it reached (-446 mV). Above this potential, the cathodic reaction became the dominant reaction. When the applied voltage reached (-380 mV) the alloy showed passivity due to the formation of oxide film and the current fluctuated and fell down into region (18 ~45) µamp. The partial passivity range extended to-288 mV. At -288 mV the passive film broke down and more corrosion took place. Top surface of 3-L layer showed better behavior as the passivity region started at lower potential and lasted longer till the sample pushed to a potential 18 mV where the oxide film broke down and pitting corrosion took place. The lower corrosion properties of substrate – SS Interface layer can be attributed to the dilution effect where the iron content is increased on expense of chromium amount, while the top surface of 3-L layer was less affected with dilution and had fewer changes in metallurgical properties. The electrochemical test is in agreement with the weight loss measurement particularly in this point.

Implication of the Study Results
This study shows the engineers and auditors that the corrosion rate of both two clad layers either of 3mm or 5mm layers deposited by SAW lays in the accepted range of engineering applications criteria. Welding parameters and the choice of appropriate flux should be considered. No concerns may be raised if all the welding process was done according to the standards. This study also implies that the full automatic process (SAW) has very limited defects and impact on the electrochemical properties and therefore to minimise the effect of dilution on corrosion properties of stainless steel used in sea water applications nevertheless the commercial usage, full automatic welding technique where all parameters can be controlled should be considered. In all cases, engineers and auditors should consider carrying out the microstructure tests to make sure the product is free from the brittle sigma phase especially where the clad product is subjected to cyclic loads and the application demands high safety standards.

Conclusion
The results of both gravimetric and electrochemical analyses consistently demonstrate that dilution marginally affects the corrosion resistance of the stainless-steel cladding, with all measured properties remaining within acceptable operational limits. This effect is attenuated with increasing cladding thickness. This study demonstrates that the Submerged Arc Welding (SAW) technique is a suitable method for applying stainless steel cladding to a low-carbon steel substrate, yielding superior corrosion resistance. SAW cladding exhibited minimal degradation of corrosion performance, effectively retaining the inherent properties of the welded stainless steel.

The results of both electrochemical and gravimetric analyses consistently show that dilution has a negligible impact on the stainless-steel cladding's corrosion resistance. with all measured electrochemical properties staying within allowable operating criteria. As the thickness of the cladding increases, the dilution effect decreases. This study demonstrates that stainless steel cladding to a low-carbon steel substrate using Submerged Arc Welding (SAW) is an effective technique as he intrinsic qualities of the welded stainless steel were successfully preserved.

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