

Development of Electropolishing-Based Corrosion Resistance Technique for Ferritic Stainless Steel

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ABSTRACT

One issue raised by the use of austenitic stainless steels in commercial vehicles is the increase in material costs. To reduce those material costs, a nitric acid electropolishing treatment was applied to SUS436L (18 Cr - 1.5 Mo - 0.4 Nb) and corrosion tests were conducted to compare its corrosion resistance to that of SUS316L (16 Cr - 12 Ni - 2 Mo). Compared to SUS316L, SUS436L subjected to nitric acid electropolishing indicated superior corrosion resistance. In addition, XPS and TEM analyses showed that while the SUS436L passivation film layer contained approximately twice as much chromium, its thickness was also generally reduced by approximately half, to 2 nm. These results suggest that electropolishing with nitric acid, which is highly oxidative, formed a fine passivation film.

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2. INTRODUCTION

Even as commercial vehicles must address issues such as compliance with diesel exhaust gas regulations and growing market globalization, corrosive environments, especially around exhaust system parts are becoming unavoidably more severe, leading to greater demand for stainless steels as a material suited to such environments.

Austenitic stainless steels, which feature excellent corrosion resistance, are commonly used as the stainless steel material in Exhaust Gas Recirculation coolers or exhaust gas treatment systems. However, the high nickel content of austenite stainless steels also creates the need to deal with issues such as material cost escalation and large price fluctuations. Although one potential solution would be to use ferritic stainless steels, which contain almost no nickel, those steels generally have lower corrosion resistance than austenitic stainless steels [1].

The present paper describes how efforts to reduce material costs led to obtaining corrosion resistance superior to that of JIS SUS316L, an austenitic stainless steel featuring high corrosion resistance, by applying an electropolishing treatment to a low-cost ferritic stainless steel immersed in an acid solution. Moreover, the estimated results concerning the mechanism underlying the improvement of corrosion resistance in ferritic stainless steel, obtained through detailed XPS and TEM analyses, are also presented.

3. CONCEPT BEHIND THE IMPROVEMENT OF CORROSION RESISTANCE

The superior corrosion resistance of stainless steel is dependent on a passivation film layer a few nanometers thick that consists of a hydrated oxide composed of chromium, oxygen, and hydroxides [2]. Therefore, electropolishing treatment conditions were assessed using individual specimens. The goals of this research project were set as 1) matching or exceeding the high corrosion resistance of JIS SUS316L (16Cr-12-Ni-2Mo) austenitic stainless steel using ferritic stainless steel, and 2) reducing material cost by 20%.

4. CORROSION RESISTANCE EVALUATION TEST

4.1. Selection of Test Materials

In light of the requirement for high weldability in stainless steels used in automobile parts, ferritic stainless steels, which have low carbon content and good market liquidity were assumed as test materials. Table 1 lists the typical content of constituents in the test materials and the SUS316L, which served as the baseline for comparison.

As for the features of selected ferritic stainless steels, JIS SUS410L (11Cr) has a chromium content of 11%, and, as the stainless steel with the lowest cost, offers the greatest cost benefit. JIS SUS436L (18 Cr - 1.5 Mo - 0.4 Nb) is a stainless steel for which improved corrosion resistance through higher chromium content and the addition of molybdenum, as well as mitigated sensitization through the addition of niobium. An electropolishing treatment was applied to both of the above ferritic stainless steels, and their corrosion resistance was compared to that of SUS316L.

Table 1. Test material constituents wt%

	C	Cr	Ni	Mo	N	Nb
JIS SUS410L	0.010	11.2	0.10	-	-	-
JIS SUS436L	0.010	18.2	0.10	1.50	0.02	0.40
JIS SUS316L	0.008	17.4	12.2	2.03	-	-

4.2. Application of the Electropolishing Treatment

Figure 1 shows the method used to apply the electropolishing treatment. The specimen connected to the positive terminal and an electrode to the negative terminal were immersed in an electrolyte solution, and a low voltage device was used to apply direct current and dissolve the surface of the specimen on the positive terminal. Unlike mechanical polishing treatments that rely on grinding or abrasion, electropolishing is an electrochemical process. Therefore, one characteristic of the process is the ability to finish the surface of the target material without inflicting physical damage such as polishing distortion [3].

Electropolishing treatments for stainless steels are typically applied to improve both design and corrosion resistance, and often use an electrolyte solution primarily composed of an aqueous phosphoric acid solution [4]. However, this research focused on the purpose of the electropolishing treatment to improving corrosion resistance and thus used aqueous nitric acid with no additives as an electrolyte solution. The selection of aqueous nitric acid was based on the supposition that choosing electropolishing treatment conditions that make use of the extremely strong oxidizing properties of nitric acid would lead to the formation of a passivation film with excellent corrosion resistance. The electropolishing treatment was therefore performed using an electrolyte solution consisting only of 20wt% aqueous nitric acid. Table 2 lists the other conditions used in electropolishing treatment.

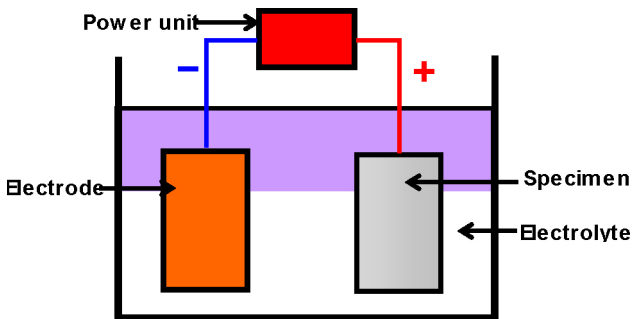


Figure 1. Schematic diagram of electropolishing process

Table 2. Electropolishing conditions

Finishing of test materials	2D finish used for both materials
Shape of evaluated materials	30 mm ² , thickness of 1.5 mm
Pre-treatment	Ultrasonic cleaning with acetone
Cathode material	Pure copper (same shape as test material)
Current density	Approx. 0.2 A/cm ²
Treatment time	Approx. 3 minutes
Electrolyte	20 w t% aqueous nitric acid
Diluted electrolyte medium	Deionized water

4.3. Conditions for Whole-Surface Corrosion Test

If use in exhaust system parts is assumed, the concentration of sulfur in the exhaust gas varies according to vehicle driving conditions, causing low to high concentrations of sulfuric acid condensation to form on the surface of the material in contact with the exhaust gas. Consequently, the concentrations of aqueous sulfuric acid applied in the whole surface corrosion test were set to 10, 20, 30, 40, 50 and 60 wt%, and each specimen was immersed under those conditions for one hour. The corrosion of the whole surface was evaluated based on the amount of weight loss before and after the test [5]. Table 3 lists the conditions for the whole surface corrosion test.

Table 3. Sulfuric acid immersion test conditions

Sulfuric acid aqueous solution concentration w t%	10	20	40	50	60
Retention temperature °C	20	40	60	70	80

4.4. Test Conditions for Pitting Corrosion

Pitting potential was measured to address concerns about snow melting agents containing chlorine causing pitting corrosion on the outer surface of exhaust system parts. Pitting potential measurements were conducted in accordance with JIS G 0577: Methods of pitting potential measurement for stainless steels.

5. TEST RESULTS AND DISCUSSIONS

5.1. Results of Whole Surface Corrosion Resistance Analysis

Figure 2 shows the results of the immersion test for each material. In the figures and tables in this paper, the abbreviation EP stands for the aqueous nitric acid electropolishing (EP) treatment. Also, the results of applying an aqueous phosphoric acid-based electropolishing treatment to SUS436L are also presented to provide a comparison of whole surface corrosion in material subjected to electropolishing using aqueous phosphoric acid. The phosphoric acid electropolishing treatment results are marked as EP using phosphoric acid.

Compared to SUS316L, SUS436L subjected to nitric acid electropolishing exhibits superior whole surface corrosion resistance. In particular, at an aqueous sulfuric acid concentration of 50 wt% and a test temperature of 70°C, where SUS316L exhibits a corrosion weight loss of 13.13%, the SUS436L specimen subjected to nitric acid electropolishing exhibits a corrosion weight loss of 0.015%.

Comparing the different electrolyte solutions also confirmed that specimens subjected to an electropolishing treatment using aqueous nitric acid had superior whole surface corrosion resistance compared to specimens subjected to the aqueous phosphoric acid-based treatment. For SUS410L, by contrast, no difference in whole surface corrosion resistance was observed regardless of whether or not the nitric acid electropolishing treatment was applied, and it was not possible to confirm that this treatment mitigated whole surface corrosion.

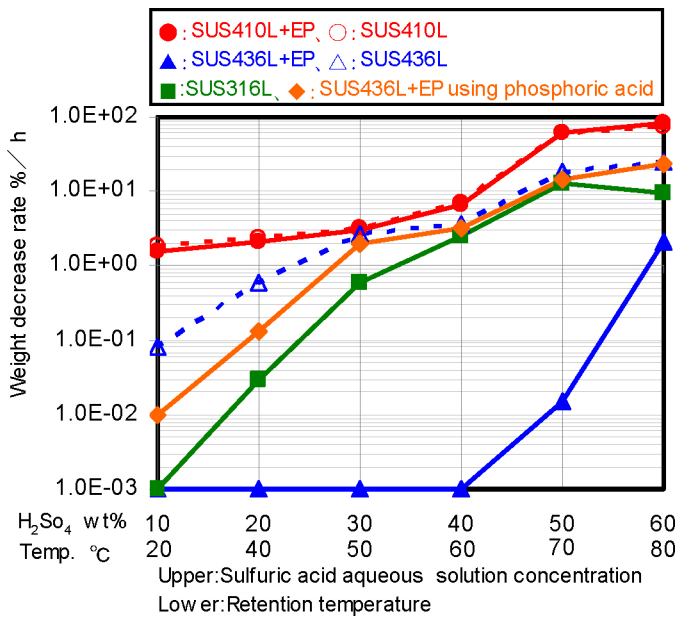


Figure 2. Sulfuric acid aqueous solution immersion test results

5.2. Results of Pitting Corrosion Resistance Analysis

Table 4 shows the results of measuring pitting potential under saltwater exposure. it indicates that the averages and standard deviations resulted from the 5 times measurements.

Table 4. Pitting potential measurement results V vs. SCE

	SUS 410L +EP	SUS 410L	SUS 436L +EP	SUS 436L	SUS 316L	SUS436L +EP using phosphoric acid
Average(N5)	0.11	0.08	0.54	0.31	0.40	0.35
Standard deviation	±0.03	±0.02	±0.02	±0.04	±0.03	±0.03

The results confirmed that for a pitting potential V_c 10, SUS436L subjected to nitric acid electropolishing rated approximately 1.35 times higher than SUS316L, while no obvious improvement in pitting potential from the nitric acid electropolishing treatment were confirmed for SUS410L. No improvements in either whole surface corrosion resistance or pitting corrosion resistance were observed after applying nitric acid electropolishing to SUS410L. The reasons behind this are presented in the observations concerning the results of the XPS analysis.

6. SURFACE ANALYSIS RESULTS AND DISCUSSIONS

6.1. Results of XPS Analysis of Element Concentration in the Depth Direction

An analysis of element concentration in the passivation film of SUS436L, in which nitric acid electropolishing was observed to improve corrosion resistance, was conducted. The distribution of the concentration in the depth direction is shown in Figure 3 for chromium (Cr2p), Figure 4 for oxygen (O1s), Figure 5 for molybdenum (Mo3d), Figure 6 for carbon (C1s), and Figure 7 for

phosphorus (P2p). The XPS analysis was performed with the ULVAC-PHI Quantera SXM. Table 5 lists the conditions used in XPS analysis of element concentration in the Depth Direction

Table 5. XPS measurement conditions

X-ray source		Al K α with 1486.6eV
X-ray introjection degree		45°
X-ray beam diameter		φ200μm
Pass energy		112.0eV
Sputtering	Ion	Argon ion
	Voltage	2kV
	Area	2mm ²
	Sputter rate	6.0nm/min (commuted by SiO ₂)

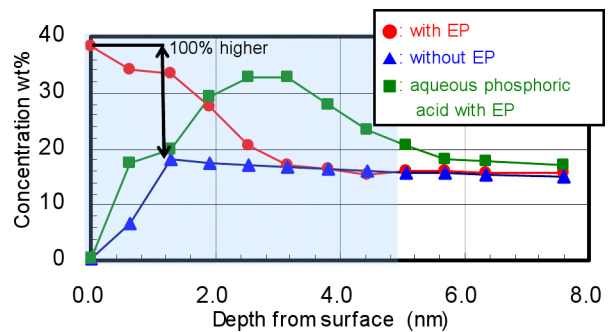


Figure 3. Relationship between depth and chromium concentration in SUS436L

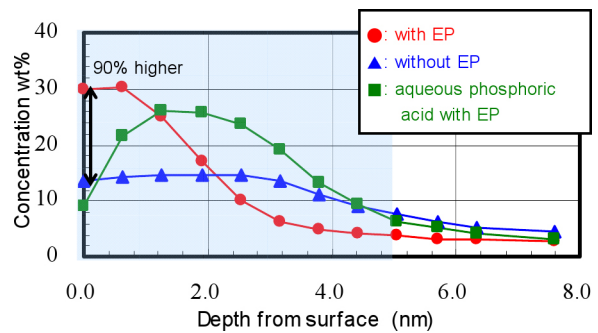


Figure 4. Relationship between depth and oxygen concentration in SUS436L

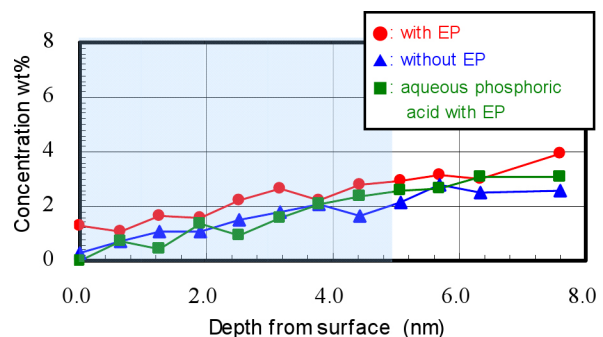


Figure 5. Relationship between depth and molybdenum concentration in SUS436L