An Investigation of Corrosion Behavior and Protection Methods for SMC Components

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Abstract: Soft magnetic composites are used for electromagnetic applications such as motors, inductors, actuators and pulse-transformers. The occurrence of corrosion in magnetic components in different environments can be a universal problem, and good corrosion protection is very important for many electromagnetic applications. This study investigated the effect of corrosion on the mechanical strength and magnetic properties of four types of SMC components when compared with Fe-Si laminated steel components. Several protection coatings were evaluated using both a Salt Spray Test and Electrochemical Impedance Spectroscopy (EIS) measurements. It was found that corrosion might decrease the mechanical strength and magnetic properties of SMC. However, the stability of magnetic properties for SMC materials is better than laminated steel sheets in corrosive environments. A water-borne single coat of paint can offer good protective properties against corrosion.

1. Introduction

SMC material is based on pure iron or iron alloy powder and has an electrically insulated layer. The mean particle sizes of powder are from 50~250 μm [1]. SMC components are produced using a powder metallurgy process so there is always some porosity in a component [2,3]. SMC components can be used for many electromagnetic applications such as motors, inductor, actuators and pulse-transformers etc. [4,5,6].

Metallic materials are usually exposed to corrosion due to chemical reactions with aqueous and atmospheric environments. The effects and consequences of corrosion are various, and the impact on the operational effectiveness and safety of equipment, or construction machines are normally much worse than the simple loss of metal mass. For example, a reduction of metal thickness can result in the loss of mechanical properties and a failed surface structure. Metallic corrosion is a common problem that we need to solve in our industrialized society [7]. Electromagnetic applications with SMC components have the potential to be an exception but sometimes different climatic conditions can cause corrosion such as sea salt.

The aim of this study is to examine the corrosion behavior of four Somaloy® component samples and compare them with laminated steel sheets using a salt spray test. Both the mechanical properties and magnetic performance of corroded samples were measured. Four different types of surface treatments, including phosphoric acid coating, sodium silicate coating, DCA-Modified silicone conformal coating and water-borne single paint coating were evaluated.

2. Experimental details

2.1 samples

Four Somaloy powders (Somaloy 700 1P, Somaloy 700 3P, Somaloy 700HR 5P and Somaloy 110i 5P) were compacted to TRS bar and toroid (55x45x5 mm) as test samples. The first three materials have a mean particle size of 250μm and Somaloy 110i 5P is 45μm. Electrical laminate sheets (MH350) were punched to form toroids (55x45x5 mm) and be used as benchmark samples.

2.2 Protection coatings

Four different surface treatments for the protection of SMC component surfaces were tested for this study and are as follows:

Phosphate coating: Phosphate coating has been widely used for the surface treatment for steel and has the ability to increase corrosion resistance. In general, this coating has the advantage of being low cost and uses simple processing [8]. For the phosphating procedure in this study, the Somaloy component bar samples were first cleaned. Then the samples were immersed in a phosphoric acid solution for five minutes. The next step was rinsing with deionized water to remove the residual acid and then the samples were dried in a furnace at 120 °C for two hours.

Sodium silicate: Sodium silicate (also called water glass) coating is frequently used as an effective corrosion inhibitor for metal and is non-toxic and low cost. The sodium silicate solution for this study used a ratio of 2:1 sodium silicate to water. The Somaloy components were heated at 150 °C for one hour. Then the samples were immersed in the sodium silicate solution for four minutes and then cleaned by paper to remove any residual sodium silicate solution. Finally, the samples were heated for hardening at 150 °C for one hour.

DCA-Modified silicone conformal coating (SCC3): DCA is a flexible, transparent and unique modified silicone conformal coating specifically designed for protection of electronic circuitry. In this test, DCA aerosol was sprayed onto the entire surface of the Somaloy component bar samples, which were dried at room temperature (around 25 °C). Then the bar samples were placed in a furnace for heat treatment at 120 °C for two hours.

Water-borne single paint coating: TEKNOCRYL AQUA COMBI 2780-91 is an air-drying, water-borne primer and single-coat paint based on acrylate dispersion and alkyd that contains active anticorrosive pigments. The paint dries quickly and has very good anticorrosive properties [9]. For application of the coating onto the samples, the sample surface was first cleaned (by detergent, water or ethanol) to remove contaminants that might be detrimental to the painting. When the samples were dried, the paint was sprayed onto the samples.

2.3 Test and evaluations

Salt spray test: This test is a standardized, accelerated corrosion test method that is commonly used to evaluate the corrosion resistance of metallic materials and surface coatings. In our test, the salt spray test was performed according to ISO 16701 in an Ascott Salt Spray Chamber. The test was repeated three times and included a 6 hour exposure to a slightly acidified solution (pH 4.2) containing 1 wt. % sodium chloride. This was done twice per week. The salt spray cycle was followed by conditioning using controlled humidity cycling between 95 % RH and 50 % RH at a fixed temperature of 35 °C.

Transverse Rupture Strength (TRS): Transverse Rupture Strength (TRS) was measured according to ISO 3995.

Hysteresis loop measurement: Magnetic toroids were used as samples for the evaluation of magnetic properties. Toroid samples have 100 drive and 100 sense turns winding. The core loss and B-H curves were measured using a Brockhaus hysterisisgraph MPG200D.

EIS measurement: Evaluation of the protective properties of the coatings mentioned above was performed using EIS measurements in a 0.1 M NaCl solution (electrolyte). Each electrochemical cell for the measurements consisted of a sample as a working electrode, a saturated Ag/AgCl electrode as reference electrode, and a platinum strip as the counter electrode. The EIS measurements were performed at the corrosion potential of the sample in the solution, using a multi-channel Autolab instrument (model: PG STAT 128N) shown in Figure 1. The AC perturbation amplitude was 10 mV and the frequency range was 104 -10-2 Hz. The diameter of the round sample was 2.5 cm and the height was around 2-3 mm, while the surface area exposed to the electrolyte was about 0.8 cm^2. Two types of treated samples, three pieces of parallel samples of each type, were measured during an exposure of 1 week. The EIS spectra were recorded at the time intervals of 1 hour, 1 day, 3 days, 5 days and 7 days. For quantitative analysis, fitting of the spectra by using an equivalent electrical circuit was made using the Nova 1.11 software.

Figure 1. Autolab instrument with 8 channels for electrochemical measurements.

3. Results and discussion

3.1 Untreated Somaloy components

Figure 2 shows photos of the four types of untreated Somaloy components before they were taken out each time from the salt spray chamber to measure the TRS values. These photos indicate that the Somaloy components have relatively low corrosion resistance and corrode fast in aggressive environments. For example, there was considerable rust on the whole surface of the S700 5P samples after only 1 day. From the change of the rust color, the reddish ferrous oxides products gradually turned into dark red ferrous ferric oxides.

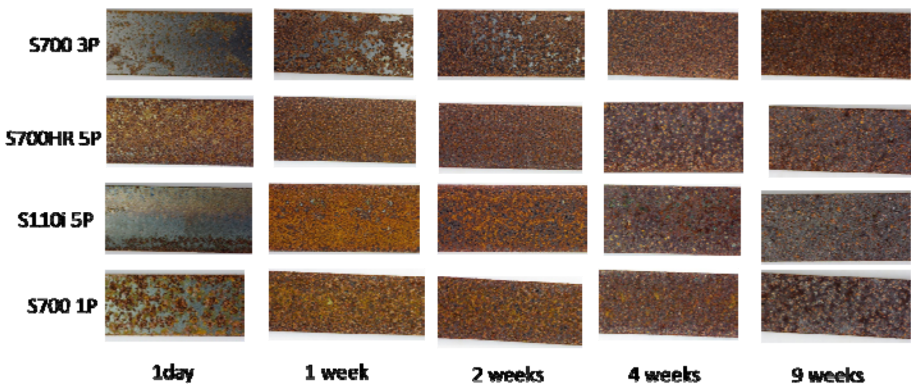


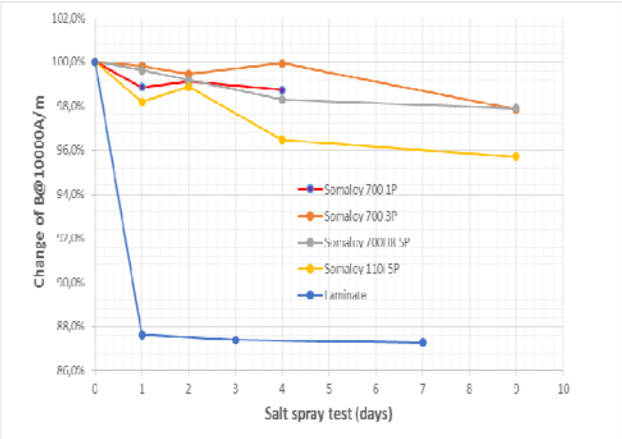
Figure 2. Photos of untreated Somaloy components corroded bar samples.

Table 1 shows the variation of TRS values for the four types of untreated Somaloy components against a timeline. The mechanical strength of S700 3P, S700HR 5P and S700 1P decreases on different levels, and after 9 weeks of the salt spray test they decrease by around 10 %, 7 % and 20 % respectively compared to the reference samples (before salt spray testing). The 5P material shows the most stable strength during the salt spray corrosion test. It is important to note that the TRS value of Somaloy®110i 5P increases during the salt spray test.

Table 1. TRS (MPa) data of untreated Somaloy components during the salt spray test.

Material	Reference	1 week	2 weeks	4 weeks	9 weeks	
Somaloy 700 3P	136	127	125	124	122	↓ 10%
Somaloy 700HR 5P	65	62	62	62	60	↓ 7%
Somaloy 110i 5P	35	38	47	46	44	↑
Somaloy 700 1P	39	37	35	33	32	↓20%

Figure 3 and 4 show the magnetic data of untreated Somaloy rings and laminated ring samples during the salt spray test. The maximum magnetic flux of 3 untreated Somaloy components with 250 µm mean particle size samples (Somaloy 700 family) remains almost the same during the first 4 weeks and decreases slightly (around only 2%) after 9 weeks of the test. The maximum magnetic flux of Somaloy 110i 5P components with 45 µm mean particle size powder decreases slowly during the corrosion test. Regarding the core losses, the values are almost same for Somaloy 700 materials after 4 weeks and increases by 2 % for Somaloy 700 HR 5P to 4 % for Somaloy 700 3P after 9 weeks. The core loss of Somaloy 110i 5P increases by around 6 % after 1 week and then it remains stable.



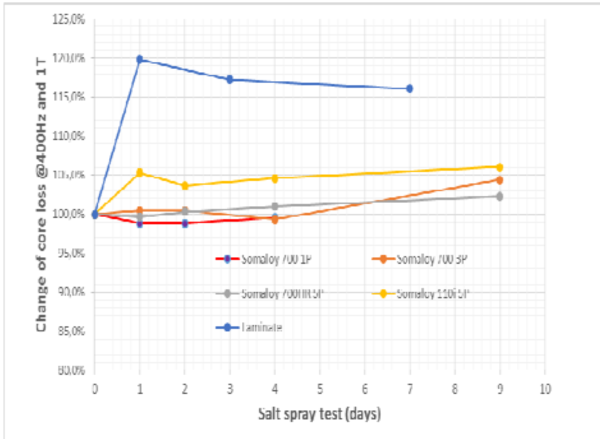


Fig. 3 and 4. Changes to the B@10kA/m core loss @ 400Hz 1T during the salt spray test.

However, the results for the laminated ring samples experience a big change compared to the reference samples. The maximum magnetic flux 10kA/m decreases by approximately 12 % only after 1 week. Its core loss increases by 20 %. The corrosion has some effect on the SMC component's TRS which is more sensitive to the surface condition. The corrosion does not have a significant effect on the magnetic properties of the Somaloy components which is more related to bulk performance. This means that the corrosion occurs mainly on the surface. Somaloy 700HR has the best stability when resisting corrosion and Somaloy 700 1P performs relatively poorly. Fine powder has little resistance against corrosion.

3.2 Surface treated Somaloy components

Figure 5 shows the photos of the Somaloy components with a phosphate coating corroded by the salt spray test. After only 1 week the ferric phosphate layer of all four Somaloy components had already been destroyed and rust was distributed across all surfaces. Figure 6 shows the images of Somaloy components with sodium silicate coating during the test. The sodium silicate coating has a different effect on the four types of Somaloy components in the corrosive environments. There were only several small parts of rust on the surface of the S700 3P samples, even after 7 weeks. S700HR 5P and S110i 5P samples corroded very fast and reddish ferrous oxides covered their whole surface after only 1 week. Some pitting existed on the surface of the S700 1P samples in the first week and this gradually increased with time until by the seventh week the rust almost covered the entire surface. All four kinds of bar samples with DCA-modified silicone conformal coating corroded quickly. After 2 weeks the ferrous oxides rust covered the whole surface as shown in figure7. Therefore, it can be concluded that this kind of coating has a low resistance to corrosion and cannot form an effective layer of protection. Figure 8 shows the photos of the Somaloy bar samples with a water-borne single paint coating during the salt spray test. From the pictures it can be seen after 5 weeks that only a minor amount of pitting appears on the surface of the four bar samples. When compared to the other three coatings, the protective effect of this paint is better and the corrosion resistance is much higher from the salt spray test.

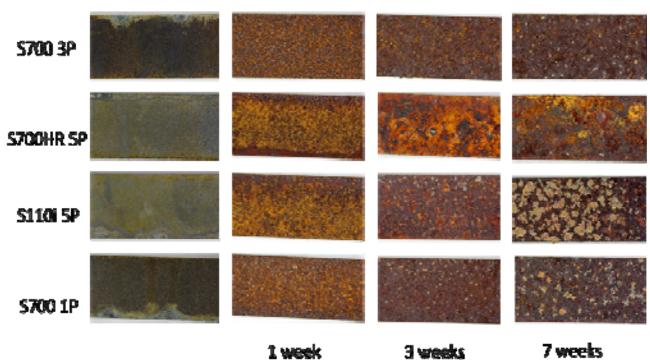


Fig. 5. Corroded samples with phosphate coating.

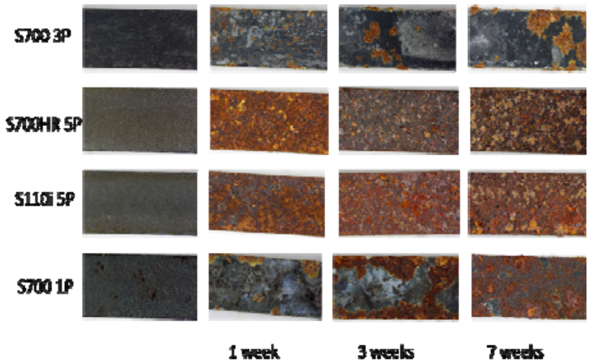


Fig. 6. Corroded samples with sodium silicate coating.

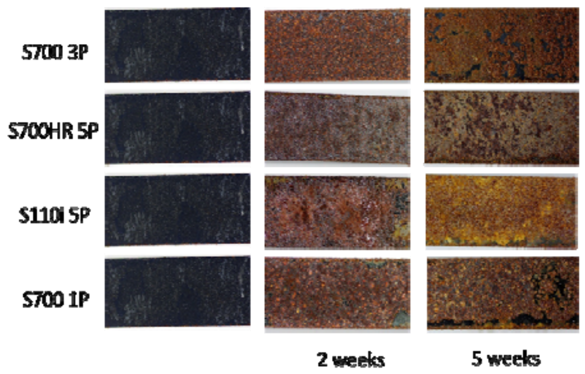


Fig. 7. Corroded samples with SCC3 coating.

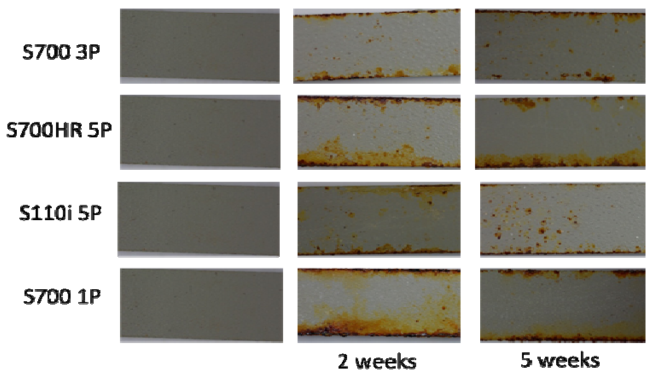


Fig. 8. Corroded samples with water-borne paint.

Table 2. TRS (MPa) data of Somaloy components with different coatings during the salt spray test.

	phosphate coating			Sodium silicate coating			SCC3 coating			Water-borne single coat paint		
Materail	1 week	3 weeks	7 weeks	1 week	3 weeks	7 weeks	Reference	2 weeks	5 weeks	Reference	2 weeks	5 weeks
Somaloy® 700 3P	135	132	127	132	130	129	136	124	122	140	136	129
Somaloy® 700HR 5P	62	62	63	63	63	61	59	58	59	65	61	61
Somaloy® 110i 5P	36	35	38	40	43	43	37	42	42	35	37	39
Somaloy® 700 1P	45	45	45	48	47	46	41	40	39	42	39	40

As discussed above, TRS is more sensitive to corrosion. Table 2 shows the change of TRS values for the four types of Somaloy components with different coatings. In comparison to the values in Table 1, the TRS values decrease slowly in table 2. This means that all four coatings have some protection effect. DCA-Modified silicone conformal coating provides the least protection. The protection of all four coatings is good enough to avoid any deterioration of magnetic properties after up to 7 weeks of the salt spray test.

3.3 EIS measurement

In recent years, electrochemical impedance spectroscopy (EIS) has been widely used in the study of corrosion processes and the evaluation of coatings in different kinds of corrosive environments [10]. Based on the results of the salt spray test, S700 3P and S700HR 5P were chosen as the substrate materials, while sodium silicate coating and water-borne single paint coating were chosen as the coatings for EIS measurements. These two coatings were chosen because of the low corrosion rate as judged from photos of the corroded samples. The EIS measurements were performed to quantitatively evaluate the corrosion resistance, and especially for comparison between the coatings. The Nyquist plot and Bode plots of the untreated S700 3P and S700 3P with water-borne single coat paint during 7 days exposure to 0.1 M NaCl solution are shown in Figure 9, and 10. Similar plots of other components can be obtained during this measurement. The figures display the EIS spectra obtained after different time intervals, showing the time evolution of the impedance response of the samples in the solution. All the spectra exhibit one time-constant feature and that is one semicircle in the Nyquist plot and one peak in the Bode plot. Therefore, the EIS spectra can be fitted by using the simple equivalent circuit, which is commonly used for spectra exhibiting one time-constant features. Results of different components - RP, which is the polarization resistance of the sample in the electrolyte and a measure of the corrosion resistance are given in Table 3.

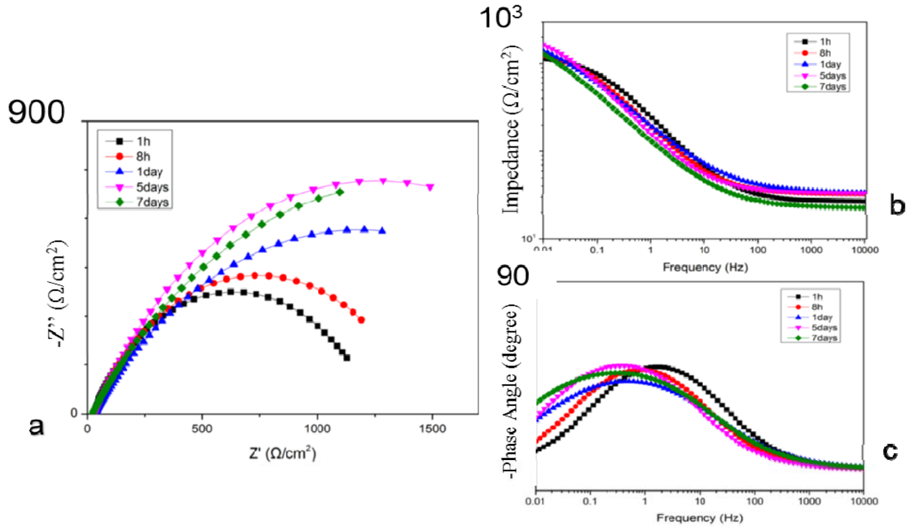


Figure 9. EIS spectra for untreated Somaloy 700 3P after exposure to 0.1 M NaCl solution: (a) Nyquist plot, (b) Impedance spectra and (c) Phase angle spectra.

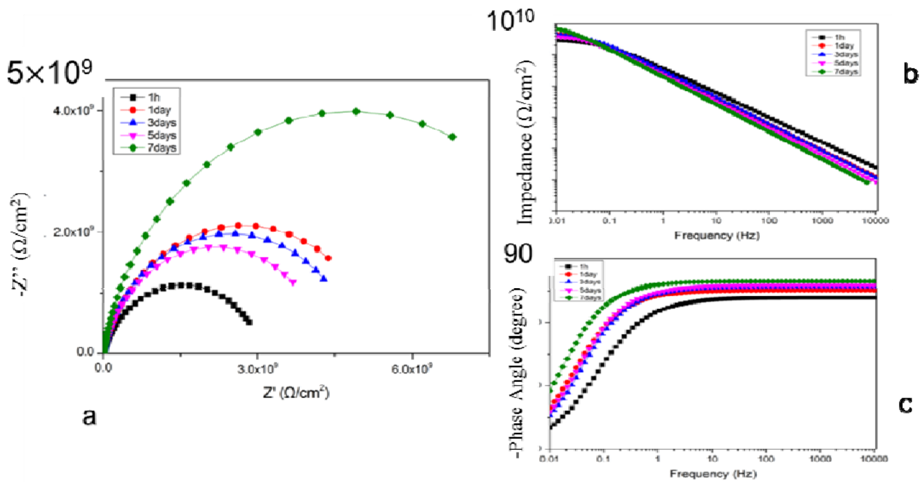


Figure. 10 EIS spectra for Somaloy 700 3P with water-borne single coat paint after exposure to 0.1 M NaCl solution: (a) Nyquist plot, (b) Impedance spectra and (c) Phase angle spectra.

Table 3. The polarization resistance of different samples in the electrolyte.

	Untreated S700 3P	Untreated S700 HR 5P	Na-silicate S700 3P	Na-silicate S700 HR 5P	Water-borne single coat paint S700 3P	Water-borne single coat paint S700 HR 5P
Time	R_P (Ω/cm²)	R_P (Ω/cm²)	R_P (Ω/cm²)	R_P (Ω/cm²)	R_P (Ω/cm²)	R_P (Ω/cm²)
1 hour	1215±7	529±195	40200±5568	2230±803	$(2.50\pm2.26)\times10^9$	$(9.85\pm6.87)\times10^9$
8 hours	1390±61	521±220				
1 day	2187±510	320±154	2827±1139	890±313	$(2.72\pm2.72)\times10^9$	$(2.67\pm3.28)\times10^9$
2 days			2063±353	689±386		
3 days			2943±677	1015±577	$(2.34\pm2.49)\times10^9$	$(8.86\pm1.06)\times10^8$
5 days	2073±768	744±306	2147±494	936±228	$(2.02\pm2.20)\times10^9$	$(4.86\pm0.62)\times10^8$
7 days	2610±1411	1075±452	2970±197	917±278	$(4.37\pm4.86)\times10^9$	$(7.06\pm0.96)\times10^8$

The R_P values for both untreated samples are low. During the following days the R_P value increased to a certain extent due to the corrosion formed on the surface that showed a limited corrosion protection effect. The polarization resistance for the sodium silicate treated S700HR 5P and S700 3P samples are larger than the untreated samples. This indicates that the sodium silicate coating on the sample surface acts as a protective film in the initial period of exposure. However, the polarization resistance decreases to the same level of the untreated samples after 1 day of exposure. It is likely that the sodium silicate protective film dissolved quickly in the electrolyte solution and then the corrosion occurred in almost the same way as the untreated samples. After several days exposure the R_P value increased slightly due to the corrosion products formed on the surface. Although the polarization resistance of water-borne single paint treated S700HR 5P and S700 3P decreased slightly over time, they are 6 or 7 orders of magnitudes higher than that of the untreated samples and the sodium silicate treated samples. After 7 days of exposure, the polarization resistance remained at a very high level, which indicates very good corrosion resistance and stability for this coating. In this case, the corrosion rate of the substrate metal is negligible. It should be mentioned that the standard derivations of the resistance values are large. This is most likely caused by uneven coating thickness and other differences between the parallel samples. A better control of the surface condition and coating thickness are desirable for achieving good reproducibility of the results. However, it can still be concluded that the water-borne single paint coating provides good corrosion resistance for the Somaloy components.

4. Conclusions

The following conclusions were drawn, based on the TRS and Hysteresis loop measurements after the salt spray test and the EIS measurements during exposure to 0.1 M NaCl solution for 7 days:

- Although the bar samples are covered by the surface coatings, the mechanical strength decreases more or less over time due to the corrosion attack by the salt spray.
- In contrast, the corrosive environments hardly influence the magnetic properties of the untreated and four treated Somaloy components.The magnetic properties of the laminated ring samples have a significant deterioration after the salt spray test. Thus, the stability of magnetic properties for Somaloy is much better than the laminated steel sheets.
- For the samples with the water-borne single paint coating, the initial corrosion resistance is 6-7 orders of magnitudes higher than that of the untreated samples. The water-borne single paint coating therefore provides very stable corrosion protection for the Somaloy components.

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