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Experimental investigation of long-term effects on temperature reliability of exothermic coating for smart railway structures with self-heating surfaces

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Abstract. Gravel scattering, which occurs from snow-ice that develops on trains during winter, is a major cause of damage to train parts. An exothermic technology that uses copper wires to solve the problem of gravel scattering is ineffective on the snow-ice produced on the surface of the trains. Therefore, studies have been conducted to overcome the weaknesses of the conventional methods and to develop a paint-type surface exothermic technology that can be efficiently applied to complicated structures. However, multi-layered paint-type coatings can lead to problems such as a delamination or exfoliation of the layers when used for a long period of time within an environment undergoing variations in temperature. Therefore, this study assesses the long-term effects of temperature on multi-layered exothermic coating technology based on nano-solutions for an application of self-heating function on railway infrastructures. To do so, we developed an exothermic coating test specimen using the paint applied to train cars and commercial nano-solutions. To conduct an experiment on accelerated aging, the specimen was subjected to regular changes in the temperature within a thermal chamber. The results revealed that there is a nonlinear decline in the performance as the specimen is worn out in comparison to the exothermic performance achieved during the early stages. Further, it is possible to identify the structural causes of the decline in performance from the specimen applied thermal load by analyzing the morphology. However, it is possible to observe a high stability from noninvasive overheating or short-circuits based on the structural changes to the coating, which are observed during the assessment of the exothermic uniformity. Therefore, it can be concluded that a multi-layer exothermic coating, which can be effectively applied as an exothermic technology based on self-heating surfaces, can be applied for a long period to prevent disasters from freezing or snow-ice in trains during winter.

Keywords: long-term reliability; exothermic coating; self-heating surfaces; cyclic thermal load; exothermic performance

1. Introduction

Numerous different safety accidents occur in railway environments during winter owing to freezing temperatures and snow-ice. For example, frozen train and screen doors are difficult to open and close, causing inconvenience to the passengers. In addition, gravel scattering (Önder and Robinson 2018) induced by high-speed trains is the main cause of damage to train parts such as windows and axle protectors. At least 60% of gravel scattering occurs during winter when snow-ice is present (Kim and Cho 2017). This also leads to other problems such as a loss of profit owing to a shutdown of the rail services, in addition to problems related to the replacement costs of the train parts. Among these problems, damage to the train windows not only leads to additional maintenance costs but is also the main cause of the decline in the credibility of the institution, being related to the psychological anxiety of the passengers. To prevent such problems and efficiently manage a railway system, new technologies for monitoring safety are continuously being developed in various ways (Liu *et al*. 2018, Li and Wang 2018, Du *et al*. 2019).

To solve the various problems that occur during winter, there have been numerous attempts to eliminate the snow-ice that appears underneath the trains, such as heating systems (Gue and Li 2013, Wang *et al*. 2018) that apply copper wires, exothermic jackets, and hot air. However, these methods require a long time to apply and are inefficient in eliminating snow-ice produced on the surface of the trains, relying heavily on manpower. The release of de-icing fluids and hot water, which is considered the most advanced technique used to eliminate ice, is applied in some

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countries such as Japan and Northern Europe. (Nilsson *et al*. 2019, Park *et al*. 2019) However, because the effects are temporary and additional problems may occur, such as the freezing of the remaining water and the possibility of water entering the electric equipment, this is not a fundamental solution for dealing with snow-ice. There is therefore an increasing need to develop a method to fundamentally solve the snow-ice problems that occur while the trains are in operation. One of the newest technologies in this regard is the use of exothermic technology that comes into effect under contact with a surface and that can release heat at all times when the trains are in operation (Yang *et al*. 2016, Jayathilake *et al*. 2019, Yang *et al*. 2019).

Unlike the past use of linear heating (Ikeya *et al*. 2017, Hu *et al*. 2018), which is a one-dimensional heating approach, surface heating has an extremely low risk of fire, and is considered an effective surface exothermic technology because it can balance out the heating of a two-dimensional space. Among the various methods applied for surface heating, studies are being conducted on an exothermic coating based on solutions incorporating carbon-based nano materials with an electrical conductivity (Lee *et al*. 2019), owing to the possibility of applying such materials to both flat and curved surfaces (Bhattacharyya *et al*. 2007, Arun *et al*. 2019). Because it is possible to manufacture extremely thin structure using nano-solutions based on carbon, such solutions can be inserted into an existing multi-layer structure. As a result, it is possible to incorporate this approach into an exothermic coating without damaging the current form. However, multi-layered structures can lead to problems such as a delamination or exfoliation of the layers based on the differences in the coefficient of thermal expansion among the materials when they are used for a long period of time within an environment undergoing changes in temperature (Li *et al*. 2012, Kumar *et al*. 2017).

In general, the functionalized smart structures like the exothermic coating for self-heating surfaces are required to have the long–term thermal reliability for field applications. For the purpose, it is necessary to investigate characteristics change of functionalized smart structures during the aging because the aging effect of exothermic coating on its durability can influence on the reliability and maintenability of smart structures (Kim *et al*. 2017). Therefore, it is highly required to investigate the long-term reliability of the specific function applied to structures in order for functionalization (Miyamoto and Motoshita 2017) of conventional infrastructures, which do not have smart functions like self-heating surfaces. In particular, to apply the exothermic coatings over the long-term, it is necessary to analyze the effects under a temperature of between -40°C to 70°C according to the technical specifications for railway vehicles (IEC 60068-2-14). Therefore, in this study, the long-term effects of temperature on multi-layer exothermic coating technology are assessed based on nano-solutions to verify the compatibility of the railroads that currently use surface exothermic technology. To do so, we first developed a multi-layered exothermic coating test specimen using paint that is applied to train cars with commercial nano-solutions, and conducted an experiment by simulating the aging of the specimen by exposing it for a long time to regular changes in temperature within a heat chamber ranging from -40°C to 70°C. Then, the changes in the exothermic performances are assessed, such as the heating rate and maximum temperature change based on each stage of the cycle, and a scanning electron microscope (SEM) is used to analyze the causes of the decline in the exothermic performance. This process has to the aim of the present study, which is to verify the long-term reliability of a multi-layered exothermic coating as a surface exothermic technology in a railway environment to prevent freezing and snow-ice damage from occurring during winter.

2. Exothermic coating structure

For this study, we developed a multi-layered plane test specimen that includes the exothermic coating layer by reflecting the paint characteristics of the multi-layered structures of the train cars. Similar to other general structures, multi-layered paint coatings are generally applied to train cars in order of primer, surfacer, base coat, and clear coat. Based on the structure, the test specimen replaced the surfacer with an exothermic layer and was developed within an area of 50 mm × 50 mm. First, the base material, which is the subject of the present study, was developed with a size of 60 mm × 60 mm × 3 mm using mild steel (SS400, POSCO Co.), which is normally applied to the bottom part of high-speed trains. We applied each layer on top of the base material with a spraying gun, as shown in Fig. 1: The order of the layer is the primer (KR-NUD-105, PPG Co.) of about 47 um thickness for an insulator, nano-solution exothermic coat (ACR70, Future-Carbon Co.) of about 32um thickness as a heating material, base coat (Base coat, KR-NUN-794S, PPG Co.) of about 42 um thickness for a painting peculiar to its own color, and polyurethane top coat (KA-900HP, Gangnam Chem. Co.) of about 50um thickness for protect from environments. In addition, a copper tape (1181, CM Co.) is applied with a 5 mm depth and 0.04 mm width to develop electrodes to energize the power between the primer and exothermic layer. A total of 21 specimens were used when considering the test cycles of the aging experiment (conducted s times) and the number of test specimens for each cycle (i.e., 3).

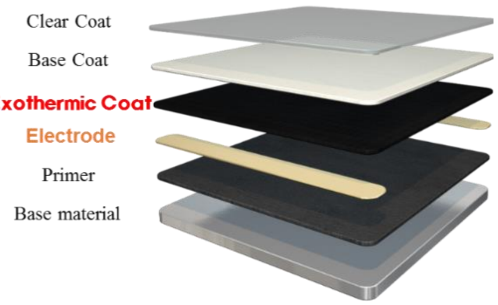

Fig. 1 Configuration of test specimen with multi-layered exothermic coating

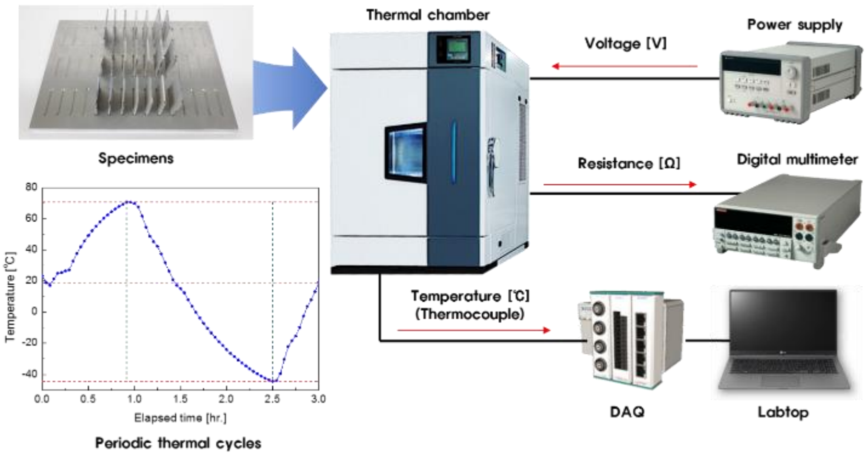

Fig. 2 Experimental setup for electrical and exothermic performance test exposed to periodic thermal cycles

3. Experimental setup

To apply exothermic coating technology on a railway environment for a long time frame, it is necessary to assess the reliability of the exothermic coating when used for a long period under the same environment with the railway. To do so, we conducted an accelerating aging experiment by reflecting the characteristics of the railroad environment with the experiment design, as shown in Fig. 2, based on the conditions of reliability required by the technical specifications for railway vehicles.

The experiment was conducted by generating periodic temperature changes ranging from -40°C to 70°C on the specimen within an environment chamber (TH-KE, Jeiotech Co.) to identify the changes in the exothermic performances of the specimen based on the progress of the cycles. The experiment went through 1,000 cycles, which is considered equal to 10 years of actual life. The conditions of the cycles for accelerated aging were room temperature (20°C) → 70°C → -40°C → room temperature (20°C), and each cycle was approximately 3 hours in length. Furthermore, to analyze the changes in the performance of the exothermic coating, we assessed the heating uniformity under a normal state and changes to the heating rate and maximum temperature change when the specimens were heated. In addition, to identify the physical evidence of the changes in the exothermic performance of the specimen, we also analyzed the morphology of the surfaces of the exothermic coating exposed to periodic thermal cycles. In addition, the changes in performance of the exothermic coating through a wearing out of the specimen and a morphology analysis showed a total of six numbers of cycles (0, 100, 300, 500, 700, and 1,000 cycles). The results at each cycle were calculated based on the mean results of three specimens.

3.1 Exothermic characteristics

It is necessary to assess the exothermic performances as time passes, and conduct an experiment on heating under the same conditions as used in prior experiments (Kim *et al.* 2019) applying a certain level of electricity 12 VC of DC (XFR100-12, Xantrex Co.) under temperatures of -20°C. To measure the heating temperature during the experiment, we used DAQ (NI9213, National Instrument Co.) with a T-type thermocouple (TC) on the surface of the specimen, under a sampling rate at 1 Hz. Then, we analyzed the changes in the exothermic performance by obtaining the heating rates and maximum temperature change by each cycle, showing the exothermic characteristics from a performance graph from the heating experiment, as shown in Fig. 3. We used a fitting line from Eq. (1) for the changes in temperature based on the time of the exothermic performance graph for a quantitative analysis.

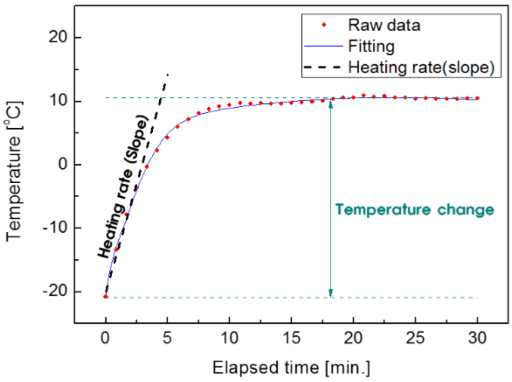

Fig. 3 Analysis method of exothermic performance with periodic thermal cycles

$$T(t) = (c_0 + c_1 t + c_2 t^2) + (c_3 + c_4 t + c_5 t^2)e^{-t} \qquad (1)$$

where, $\boldsymbol{T}$ refers to temperature, $\boldsymbol{t}$ refers to the elapsed time, and $\boldsymbol{c}_i$ (i = 1, 2, 3, 4, 5) is the coefficient.

We assessed the stability of the heating under a normal state to analyze the changes in the performance based on the locations within the test specimen, and the macroscopic exothermic performances such as the heating rates and maximum temperature change.

For the specimen at each stage of the aging cycle, when the temperature of the specimen reached the steady state after being supplied with 6V of DC at room temperature, as shown in Fig. 4, we obtained thermal images on the surface of the specimen using a thermal imaging camera (TESTO 882, Testo Co.) and analyzed the heating uniformity using

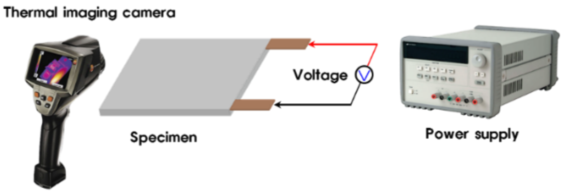

Fig. 4 Experimental setup for exothermic uniformity test

statistic techniques.

To assess the uniformity of the heating from the thermal images, we used two types of statistical technique (skewness and kurtosis). First, skewness, as shown through Eq. (2), refers to the deviation of the data within the distribution in comparison to the median value. In detail, a skewness value of zero indicates that there is a normal distribution, a negative value refers to a distribution with values greater than the median, and a positive value refers to a distribution with values lower than the median.

$$Sk = \frac{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^3}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^2}\right)^3} \tag{2}$$

where, N refers to the number of total data, X_i refers to the data, and $\bar{X}$ refers to the mean.

Kurtosis, which is shown in Eq. (3), indicates the cluster of the data. In detail, a Ku value of 3 refers to a regular distribution, a value of less than 3 indicates a dispersed distribution in comparison to a normal distribution, and a value of greater than 3 shows a clustered distribution in comparison to a normal distribution.

$$Ku = \frac{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^4}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^2}\right)^2} \tag{3}$$

where, N refers to the number of total data, X_i refers to the data, and $\bar{X}$ refers to the mean.

3.2 Morphology

In general, all materials decline in performance as time goes on, and it is necessary to understand the mechanism behind the aging process to analyze the causes of such a decline. However, it is impossible to distinguish the wearing out of the exothermic coating used in this study with the naked eye because the exothermic layer is within a multi-layered structure.

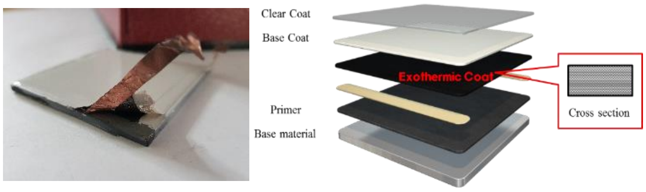

Fig. 5 Sample (left) and morphology target (right) of exothermic coating with thermal cycle changes

Therefore, to investigate the causes of the decline in performance of the exothermic coating as time passes, it is necessary to analyze the morphology of the exothermic layer of a structured multi-layered exothermic coating. For a morphology analysis of the exothermic layer of the surface, as shown in Fig. 5, an exothermic coating with a multi-layered structure is first identified within a liquid nitrogen environment of each specimen at each cycle, the coating surface is extracted using multi-layered structures, and a scanning electron microscope (SEM) is applied for the analysis.

4. Test results

The specimen is worn out for up to 1,000 cycles, divided into six sections, and the exothermic performances in each section are assessed as time passes. As mentioned in section 3.1, the items used to assess the exothermic performances were the heating rate and maximum temperature change. The results of assessing the exothermic performances based on the heating rate and maximum temperature changes of each specimen are shown in Figs. 6 and 7.

The exothermic performance of each specimen shows a similar tendency in a macroscopic point of view though there are both performance difference of 20-30% and tendency difference with aging cycles among 3 specimens.

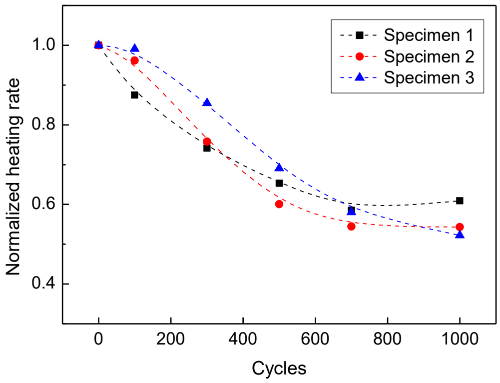

Fig. 6 Normalized heating rate of each exothermic coating specimen with thermal cycle changes

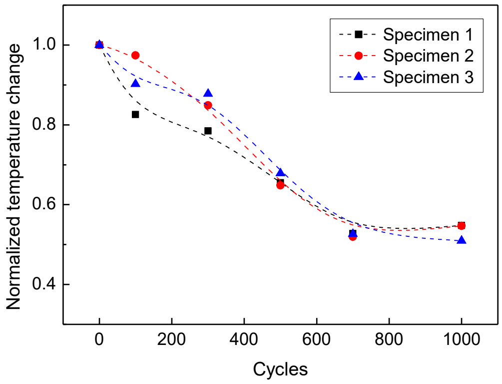

Fig. 7 Normalized temperature change of each exothermic coating specimen with thermal cycle changes

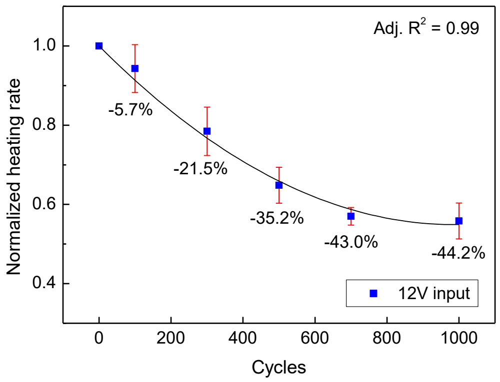

Fig. 8 Mean result of heating rate with thermal cycle changes

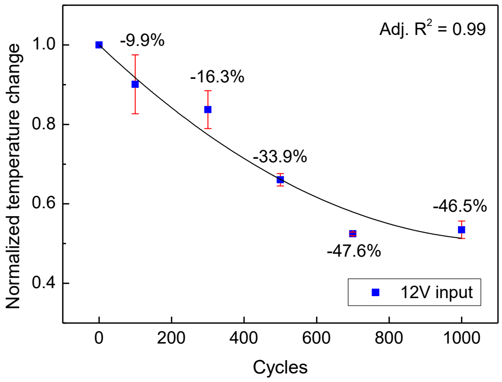

Fig. 9 Mean result of temperature change with thermal cycle changes

Those seem to be caused by manufacturing quality issues, that is lack of uniformity due to hand-spray method, rather than specific physical meaning. In other words, a quantitative assessment of the all specimens is required because of the performance deviations by the differences in fabrication.

Therefore, the study used the mean results of the three specimens in order to investigate tendency for each section of the applied cycles as shown in the Figs. 8 and 9. Both graphs show the relative rates and changes in comparison to the early performances (zero cycles), and as shown in the figures, both graphs are nonlinear (approaching a quadratic performance, where Adj. $R^2 = 0.99$) as the number of cycles increases, resulting in a decline in performance. Although there are slight differences between the two, the decline in exothermic performance as indicated by the two graphs are generally similar, and there is an approximately 45% decrease in performance in comparison to the early performances after 1,000 cycles.

There is a significant decline in performance during the early cycles, and the decreasing rates have greatly declined after approximately 700 cycles, saturated to a certain level.

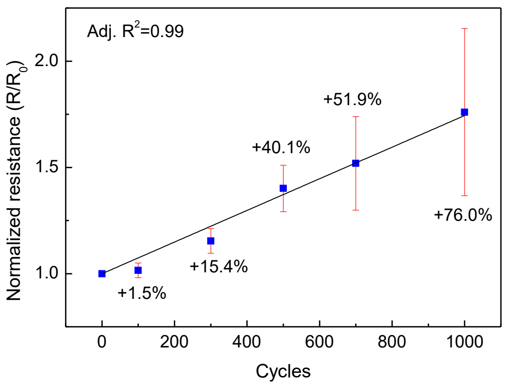

Fig. 10 Electrical resistance change of exothermic coating exposed to periodic thermal cycles

To identify the causes of the decrease in performance of the exothermic coating as time passes, we have inferred the changes in the exothermic performances based on the changes in the electrical resistance measured from each stage of the cycles. We measured the resistance of three specimens from each stage of the cycles at room temperature (approximately 20°C) using a 2-point probe method with a digital multimeter (Keithley 2000, Keithley Co.) and calculated the mean. As shown in Fig. 10, the resistance of the specimen demonstrated a linear increase, though resistance variations of specimens are also increase as periodic thermal cycles are applied.

Based on the results, it is possible to estimate the nonlinear changes in the exothermic performance using the electrical correlation equation (Redondo *et al.* 2018) for the resistance of the polymer levels, as shown in Eqs. (4) and (5).

$$q = \frac{V^2}{R}\exp\,(nV) \tag{4}$$

$$\frac{q_{cycle}}{q_0} = \frac{1}{\frac{R_{cycle}}{R_0}} \tag{5}$$

where, q refers to electricity (W), V refers to voltage (V), R refers to the electrical resistance (Ω), and n refers to the proportional constant.

In addition, because an increase in the resistance may be considered indirect evidence of the decrease in the exothermic performance, we analyzed the morphology of the exothermic layer using an SEM to identify the direct causes of such a performance decline. As shown in Fig. 11, it is possible to identify a type of structural flaw such as a cutoff of the network through SEM images of 1,500 magnifications during each stage of the cycle among exothermic materials that have exposed through 300 cycles when compared to SEM images of pristine specimens.

These small flaws increase in size or frequency under more cycles. This is different from Figs. 8 and 9, as a significant decline in performance occurs initially, ultimately leading to a certain value in the following cycles. In other words, to investigate the changes in morphology related to the decrease in the exothermic performance occurring under 300 cycles, a more detailed analysis should be conducted.

The decline in exothermic performance is considered as the changes in normalized performance of the entire area of a specimen. The differences in the performances within the locations of the surface are extremely important for

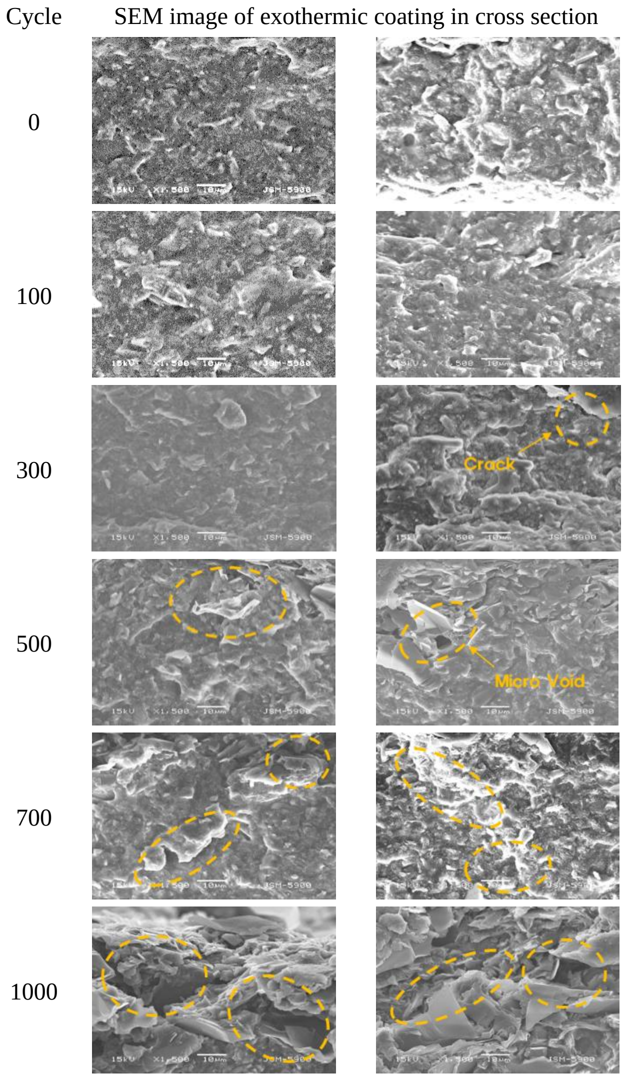

Fig. 11 Morphology of exothermic coating with thermal cycle changes

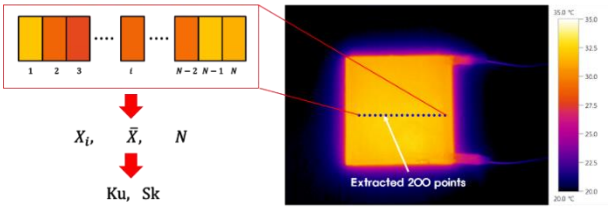

Fig. 12 Extracted points line of exothermic coating specimen in thermal image

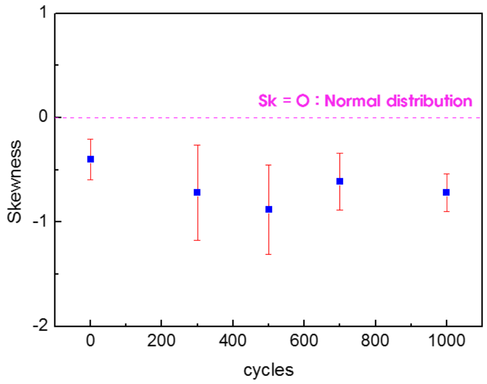

Fig. 13 Skewness of statistical evaluation for exothermic uniformity

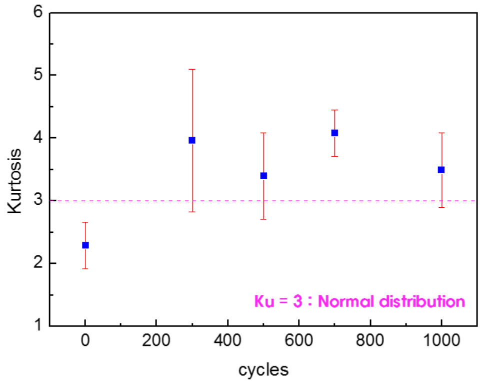

Fig. 14 Kurtosis of statistical evaluation for exothermic uniformity

exothermic technology applied to a large surface such as an exothermic coating. For a more detailed analysis, we assessed the exothermic characteristics based on the location within the specimen, that is to say, the heating uniformity, using thermal imaging cameras.

It was possible to obtain thermal images of the surfaces of the specimen when it reached a steady state at the maximum temperature after inserting DC 6V at room temperature (approximately 20℃), which is identical to the test condition used to measure the resistance. Considering the number of pixels of the thermal images, 200 points were extracted from the middle lines of each electrode on both sides, as shown in Fig. 12, to obtain data on the temperature.

The observation for the heating uniformity was conducted after 300 cycles, which was the start of the structural changes based on the results of the SEM analysis. We analyzed the skewness and kurtosis using the mean values of the temperature data from three specimens, as shown in Figs. 13 and 14. In terms of the skewness, as shown in Fig. 13, all of the values were less than zero, which means that the dispersion is focused on higher temperatures than the median, and the skewness was maintained at a certain level (-0.88 ~ -0.40) without significant changes with aging. In other words, the results of analyzing the skewness revealed that the performance of heating uniformity is maintained at a certain level even after aging proceeds in comparison to the early stages.

For kurtosis, the results show a value of 3 greater than the initial values; in other words, there is an increase in the cluster of data, as indicated in Fig. 14. This may be due to the fact that, as time passes, the exothermic performances decline, along with the target temperature of the specimen, resulting in a decrease in the differences in temperature among the locations of each specimen. Furthermore, as the Kurtosis from the repeated cycles was within a certain range (2.29 ~ 4.08), it can be concluded that there are no effects caused by aging.

In summary, there are no problems affecting the performance as time passes, such as an overheating in a particular section or circuit problems in terms of the heating stability. Further, the performances of the specimens are decline of about 45% after 1,000 cycles. However, the exothermic performances of specimens showed temperature change of avg. 17 degrees under applied voltage of 12 DC though those are exposed to cyclic thermal load of 1,000 cycles (10 years in field application). That is high enough to prevent objects from icing if we consider an average temperature (-2 degrees C) in winter season of South Korea. Besides, the exothermic coating technology might be used for a longer time though its performance declines with thermal cycles because the target temperatures can be manipulated by raising voltage.

5. Conclusions

This study assessed the long-term reliability of the exothermic coating required to apply the exothermic coating technology for a long period in a railroad environment. To do so, an experiment of accelerated aging was conducted through 1,000 cycles within a heat chamber reflecting the temperature of a railroad environment based on the technical specifications for railway vehicles using the test specimens with an exothermic coating. Afterward, the study assessed the exothermic performances of the exothermic coating by each stage of the cycles, and used an SEM to analyze the morphology of the surfaces of the exothermic layers to analyze the causes of changes in the performance.

The results indicate that there is a nonlinear decline in the exothermic performance as the specimen is worn out in comparison to the exothermic performances during the early stages (0 cycle), and there was a decline of approximately 45% in performance after 1,000 cycles. There was a significant decline in performance during the early cycles, and the decline rates greatly decreased after approximately 700 cycles. The decrease in performance may be indirectly inferred from the changes in the resistance of the specimen, and it was possible to identify the structural causes of the decline of the exothermic performances for specimens exposed to thermal load over 300 cycles by analyzing the morphology for the exothermic layers using an SEM. However, because there were no particular changes in the morphology from the specimen exposed to less than 300 cycles, which showed significant declines in the exothermic performance, it was necessary to conduct a more detailed analysis. In addition, it was possible to realize that the factors of decline of the structural performance, which can be identified from the morphology, do not affect the heating uniformity related to an overheating, or the short-circuits, by analyzing the skewness and kurtosis.

Therefore, it was possible to conclude that a multi-layer exothermic coating as the functionalized smart structures based on self-heating surfaces can be used for the long-term in the railway infrastructures to prevent disasters from freezing or snow-ice during winter.

Acknowledgments

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