Novel Rail Stress Measurement Technique using Piezospectroscopy

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Abstract

Photoluminescence piezospectroscopy (PLPS) technique is a laser-based non-contact non-destructive technique to measure the stress in Al\(_2\)O\(_3\) (alumina). By irradiating laser onto the surface of alumina, the stress level can be calculated. Thermite welding is one of the most popular welding technique in rail installation. The reaction produces iron and alumina between the ends of two rails. In this study, a feasibility study has been performed to use the alumina in thermite welds as a stress sensor using PLPS technique. A rail specimen, that was in service condition, has been prepared to experimentally validate the feasibility. The microstructure is first investigated using SEM and EDX. Then, uniaxial compression tests have been performed to small pieces of the thermite weld specimen to investigate the piezospectroscopic effect of alumina in thermite rail. The experimental results show that the novel rail stress measurement technique using PLPS has a high possibility to measure the stress in rail without any sensor installation and contact.

1. Introduction

Today railroad lines are mostly constructed as Continuous Welded Rail (CWR) thanks to its advantages such as smooth ride, increased rail life, reduced track deterioration and less maintenance. Although CWR is widely used, it has a key issue, that is a train track misalignment caused by thermal longitudinal forces. In a severe condition, a track misalignment can cause a train derailment (1). Monitoring the thermal longitudinal forces is, therefore, important for rail safety. The longitudinal force can be expressed by (2):

\[
F = \alpha EA_r (T_N - T_R)
\]

(1)

where, \(F\) is longitudinal force (N), \(\alpha\) is coefficient of thermal expansion (°C/m), \(E\) is modulus of elasticity (N/m\(^2\)), \(A_r\) is rail cross-section area (m\(^2\)), \(T_N\) is rail neutral temperature (RNT) (°C) and \(T_R\) is rail temperature (°C). RNT, that is the temperature at which has no longitudinal stress (3), needs to be predetermined to calculate the longitudinal force. However, it is difficult to determine RNT since its value varies depending on the shape and length of the track. There are various studies looking for practically applicable techniques for the absolute rail longitudinal force measurement or RNT determination, but the techniques are still unproved to be practically applied in the field without traffic interruption or rail system change. Therefore, development of non-contact passive absolute stress measurement technique is necessary for rail longitudinal force monitoring.

Photoluminescence piezo-spectroscopy (PLPS) is a potential NDT technique that can measure absolute stress in rail. Here, photoluminescence (PL) is a result of light emission process from any form of matter after the absorption of photons, and it can be generated when a sample is irradiated by a laser. Using the spectrum, the molecular
structure of a material can be identified. In addition, the stress state of the material can be also determined particularly for $\alpha$-Al$_2$O$_3$ (alumina). It is known as photoluminescence piezo-spectroscopy (PLPS) and widely used to determine the residual stress in thermal barrier coating (4)–(7). A typical PL spectrum has two distinguishable peaks of R1 and R2 lines at the wavenumbers of 14,403 cm$^{-1}$ and 14,433 cm$^{-1}$, and its peaks will be shifted left or right side from the stress-free spectrum when compressive or tensile stress is applied at the sample, respectively. Based on the phenomena, the stress level in alumina can be calculated.

Thermite welding, also known as exothermic welding, is a wide-gap welding technique, filling the gap between ends with cast iron. Thermite welding is one of the most popular welding process in rail installation and repair. In addition, it is well known that iron and alumina are produced in rail during the thermite welding process. Thus, it has a possibility to use the alumina as a sensor for measuring longitudinal stress in rail.

In this study, a feasibility study has been therefore performed to use the alumina in thermite welds as a stress sensor using PLPS technique. A rail specimen, that was in service condition, has been prepared to experimentally validate the feasibility. The microstructure is first investigated using SEM and EDX. Then, uniaxial compression tests have been performed to a small piece of the thermite weld specimen to investigate the piezospectroscopic effect of alumina in thermite rail.

2. Chemical composition investigation of thermite welded rail

2.1 Microstructure of thermite welded rail

Thermite welding is one of the most popular welding process in rail installation and repair (8). Although thermite weld has several disadvantages such as long welding time and poor quality of the weld, it is still widely used in the railroad industry thanks to its high portability, mobility, cost-effectiveness and less needs of operator’s skill (8)–(10). In thermite welding process, highly reactive fine aluminium powder reduces the oxide of iron oxide, by producing high temperatures up to 2200°C. The chemical reactions can be expressed by (11):

$$\begin{align*}
Fe_2O_3 + 2Al & \rightarrow 2 Fe + Al_2O_3 + 181.5 \text{ kcal} \\
3Fe_2O_3 + 8Al & \rightarrow 9 Fe + 4Al_2O_3 + 719.3 \text{ kcal}
\end{align*}$$

The reaction produces iron (Fe) and slag (Al$_2$O$_3$). In order to experimentally understand the microstructure of thermite weld, a portion of a rail specimen that was in service condition, was prepared including thermite weld zone, having dimension of 14.5 mm x 12.7 mm x 20.6 mm as shown in Figure 1. Then, the sample was mechanically polished. Here, the protruding section in the middle of the sample is the welded zone. Figure 1(b) shows the cross-section of the sample. The weld metal, heat-affected zones (HAZ) and parent material are clearly distinguishable by the naked eye in the figure.

(a) The surface of a rail specimen  (b) The inside of a rail specimen
The microstructure of thermite weld in rail has been investigated using Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray spectroscopy (EDX). Figure 2(a) shows the secondary electron image of the thermite weld. Void and black dots are found in the electron images. For the detailed chemical characterization of the voids and black dots, EDX line scanning was performed to the voids as well as the parent material along the red solid line as shown in Figure 2 (b) which is a backscattered electron image. Here, the black dot and white parts represent a void and parent material, respectively. Figure 2(c) shows the results of EDX line scanning. The x- and y-axis indicate the scanning distances and atomic percentages, respectively. Blue, yellow and red lines indicate the atomic percentage of Fe, Al and O. It shows that the lower part of the void scanned by EDX is a mixture of aluminium and oxygen which is alumina.

Figure 1. Rail specimen welded by thermite weld technique

2.2 Alumina distribution in thermite welded rail

In this study, a portable spectroscopy system was combined with triaxial motor stages to automatically collect PL spectra. To generate the PL signals, the excitation source was produced by a diode laser, having a wavelength of 532nm. The laser was transmitted along a fiber optic probe and then irradiated for 10 seconds onto the surface of the thermite weld. Finally, PL spectra were collected using a spectrometer as shown in Figure 3(a).

To investigate the distribution of alumina in thermite weld, alumina distribution map is drawn with the Signal to Noise Ratio (SNR) of R1 and R2 lines of alumina, and it is plotted over the photograph of inner/outer surface of the rail specimen as shown in Figure 3(b-c). Based on the alumina distribution maps, it is found that alumina particles were mostly distributed in the weld metal, and some portions of alumina particles existed in HAZ as well. The SNRs of alumina are mostly in the range of 10 to 30, so its detectability is still acceptable although the integration times were just 10 seconds.
3. Absolute stress measurement in rail using PLPS technology

3.1 Stress-free statement of alumina in thermite weld

Measuring absolute stress is one of the advantages of PLPS technique. The absolute stress of alumina in thermite welds can be calculated by knowing the stress-free state of alumina. The stress-free state can be accomplished by pulverizing the thermite weld since a powder is genuinely stress-free. Figure 4(a) shows before and after pulverizing the thermite welds. To generate the PL signal, the powder-form of thermite weld was irradiated by a 532nm laser. The PL spectrum was then collected. The wavenumbers of the R1 and R2 lines for the stress-free state were found at 14,403.9 cm\(^{-1}\) and 14,434.0 cm\(^{-1}\), respectively as shown in Figure 4(b). By comparing the wavenumbers to the one of 99% purity polycrystalline alumina powder, the non-presence of chemical shifts was ascertained. Thus, the absolute stress in the rail thermite weld can be calculated by subtracting the wavenumber of stress-free state from the one of stressed state, that is the wavenumber shifts.

3.2 Uniaxial compression test

The piezo-spectroscopic coefficient of alumina in rail thermite weld is calculated by performing uniaxial compression tests with a thermite weld specimen, having the dimensions of 15.2 mm x 12.7 mm x 19.6 mm as shown in Figure 5(a). First, a specimen was located on the bottom plate of a loading frame, and then 532nm laser irradiated onto the specimens. Next, the laser focusing spot and focal length were manually adjusted to have a high PL intensity. Uniaxial compressive loads were then gradually applied to the specimen for 23 MPa per step, up to 1.2 GPa at a loading rate of 0.8 MPa per second. For all loading steps, the specimen was stabilized at a stationary stress state for one minute before collecting a PL spectrum to have uniform stress distributions in the specimen. The PL spectra were collected at each loading step and analyzed by performing spectral deconvolution with two Lorentzian curves in order to distinguish the R1 and R2 lines.
Wavenumber shifts at each loading step are presented in Figure 6. Here, blue and red solid lines indicate the wavenumber shifts of R1 and R2 lines, respectively. Figure 6(a) shows the wavenumber shift for entire loading steps. Non-linear behavior of wavenumber shift was observed beyond the applied compressive stress of 670 MPa. The green-colored boxes indicate the linear range of wavenumber shifts. The twice enlarged graphs of the linear range are presented in Figure 6(b). The linear least squares method was used in order to find the regression coefficients by assuming the uniaxial compressive stress and wavenumber shift have a linear relation. The regression coefficients are according to the equation:

\[ y = a \times \sigma + b \]  

(3)

where, \( y \) is the wavenumber shift (cm\(^{-1}\)), \( \sigma \) is the uniaxial compressive stress (GPa), \( a \) and \( b \) are regression coefficients for the linear least squares method. Table 1 shows the calculated regression coefficients for R1 and R2 lines, and the linear regression results are plotted as the black-dashed lines in the Figure 6. Here, the coefficients of ‘a’ are the slopes of the fitted lines, and its values indicate the relation between uniaxial compressive stress and wavenumber shift which is effective piezo-spectroscopic coefficient of alumina in the rail thermite weld. The coefficients of ‘b’ are the y-intercepts of the fitted lines, and its values indicate the levels of initial stresses which is residual stresses in rail thermite welds.

\[
\begin{array}{|c|c|c|c|}
\hline
 & \text{# of data points} & a (\text{cm}^{-1}/\text{GPa}) & b (\text{cm}^{-1}) & \text{R-square} \\
\hline
\text{R1 line} & 30 & -7.02 & 14404.6 & 0.9558 \\
\text{R2 line} & 30 & -5.50 & 14434.5 & 0.9536 \\
\hline
\end{array}
\]

In order to determine the effective piezo-spectroscopic coefficient and measure the initial stress of rail thermite weld, thirty (30) data points were selected. The effective
piezo-spectroscopic coefficients of R1 and R2 lines are $-7.02 \text{ cm}^{-1}/\text{GPa}$ and $-5.50 \text{ cm}^{-1}/\text{GPa}$ respectively, having negative slopes that is compressive stress since the R1 and R2 lines of alumina shifted to the left side of initial stress. The y-intercepts of R1 and R2 lines are 14404.6 cm$^{-1}$ and 14434.5 cm$^{-1}$, respectively. In addition, it is found that R1 and R2 lines of wavenumber-stress curves are fluctuated due to the non-uniform distribution of the applied stress within the rail thermite welds (7).

Based on the findings above, it is concluded that, although there is no applied stress, R1 and R2 lines have initial wavenumber shifts, and its presence indicates that the rail thermite weld had a residual stress created during the welding process. Once a compressive stress of 670 MPa applied to the specimen, the wavenumbers of R1 and R2 lines shifted in 4.5 cm$^{-1}$ and 3.5 cm$^{-1}$ respectively to the negative direction of stress-free state. Here, the behaviour is equal to the one of pure alumina in terms of the shifted direction (7). The wavenumbers of R1 and R2 lines were almost linearly shifted to negative direction while the uniaxial compressive stresses were gradually increased up to 670 MPa, and then the wavenumbers were abruptly shifted to the positive direction due to the material yielding. Therefore, the absolute longitudinal stress in rail can be calculated by knowing both the effective piezo-spectroscopic coefficient and level of residual stress in thermite welds.

4. Conclusion

In order to determine the feasibility of using thermite weld as a passive in-situ absolute stress sensor to measure thermal longitudinal forces in rail, two experimental tests were performed in this research. First, the microstructure of thermite weld is investigated by using SEM, EDX, and then the distribution of alumina in thermite weld is also investigated by using PL spectroscopy. It is found that the many alumina particles are distributed in rail thermite weld, and the PL intensity is high enough to be measured. Second, the piezo-spectroscopic coefficient of alumina in rail thermite weld is calculated by applying uniaxial compressive stress. The piezo-spectroscopic coefficients of alumina in rail thermite weld of R1 and R2 lines are $-7.02 \text{ cm}^{-1}/\text{GPa}$ and $-5.50 \text{ cm}^{-1}/\text{GPa}$, respectively, having a linear relation between the wavenumber shift and uniaxial compressive stress up to 670 MPa. Therefore, it has a strong possibility to measure the thermal longitudinal stress in rail using rail thermite weld. Further study will include for volume fraction of alumina in thermite weld.

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