Investigation of abnormal corrosion of 10.5 – 12.5 chromium ferritic stainless steel used to fabricate railway coal wagons

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Abstract: The 10.5 – 12.5 per cent chromium ferritic stainless steel has attained success as a material used to manufacture and refurbish coal wagons. It was designed to be a low-cost material making use of the minimum chromium content required to impart acceptable corrosion resistance. There was a sudden occurrence of uniform corrosion of coal wagons manufactured between the year 2015 and 2016. This study focuses on investigating abnormally corroded wagons that are manufactured using the ferritic stainless steels. Furthermore, the exposure and salt spray tests were conducted on different consignments. The optical microscope was used to conduct a metallographic examination and chemical analysis was conducted to compare different consignments ferritic stainless steel. The root cause analysis on the plate from in-service wagon indicated that the material was indeed ferritic stainless steel and the surface roughness test showed some presence of pits on the surface of the plate. The experimental results of the different consignments indicated that one plate was dark grey which corroded quite significant during corrosion testing, whilst the other was bright grey which showed a lower corrosion rate.

1 Introduction
Ferritic stainless steel with 10.5-12.5 percentage chromium is recognised as the utility stainless steel consisting of good weldability and mechanical properties [1, 2]. The most commonly used alloying elements used in stainless steel making include chromium and nickel this contributes greatly to the corrosion resistance by forming a thin invisible protective and adherent oxide layer on the surface of the metal [3, 4]. Amongst many other applications, this utility stainless steel has achieved great success as a material of construction in the manufacturing of coal wagons for the railway industry in the last three decades [1, 2].

The first wagons manufactured out of this stainless steel were placed in-service in the year 1985, in the South African railways [2]. Generally, the lifespan of these coal wagons extends to over 30 years due to its excellent corrosion and abrasion resistance [8], however, the wagons that were manufactured between the year 2015 and 2016 showed a rather interesting red oxide layer soon after exposure to the in-service conditions. Considering that prior to this period there have not been any records of this abnormal corrosion on the coal wagons, this discovery was rather abnormal and intriguing as it is scientifically known that the stainless steel does not show such type of oxide in its nature.

A plate was then sectioned from one of the wagons which were put in-service for further examinations. Furthermore, two consignments of ferritic stainless steels plates were supplied and from this, it was also noted that the one consignment consisted of dark grey coloured ferritic stainless steel and the other one consisted of bright grey stainless steel. This raised an alarm as the ferritic stainless steel supplied in the past was bright grey in colour, therefore an investigation was also conducted to further understand this difference in colour of the ferritic stainless steel. The aim of this investigation is to establish the root cause of the sudden abnormal corrosion of the ferritic stainless steel. The findings
of this investigation will assist in identifying inferior stainless steel for the manufacturing of the coal wagons.

2 Methodology

The plate sectioned from the in-service wagon was subjected to visual examination to study the surface defects, chemical analysis to determine the type and grade of the ferritic stainless steel, surface roughness test to measure the size of the surface defects and microscopical analysis to examine the microstructure of the material. Two plates from different consignments were taken from the stores and tested (see figure 8 and 9). The bright grey and dark grey plates were marked A and B respectively. Test samples were sectioned and prepared for chemical analysis, microscopical examination, corrosion testing and x-ray diffraction analysis. Test samples were also subject to corrosion testing such as exposure test and salt spray test. Corrosion tests were carried out under a controlled laboratory environment to assess the corrosion properties of the plates test sample. The exposure test was done in accordance with specification ASTM G31-72 and G1-90 to compare the corrosion properties of the two plates. Test samples for the exposure test were prepared and immersed in a solution of 3.5% NaCl for 336 hours at room temperature. The test samples were then removed, washed, rinsed with ethanol, oven dried and weighed. Furthermore, two test samples were tested in the salt spray cabinet according to ASTM B117 where a consistent salt spray of 3.5% NaCl was applied.

3 Root cause analysis

This section focuses on the investigation of the causes of the abnormal corrosion on the coal wagons. Figure 1 below shows ferritic stainless steel plate that was used on the wagon.

![Figure 1. Corroded ferritic stainless steel plate as obtained from the in-service wagon.](image)

3.1 Surface roughness

The surface roughness of the in-service plate was analysed using a confocal laser microscope. Figure 2 and 3 shows the contour and 3D profile of the sample as obtained. This figure clearly indicates the presence of pitting and corrosion attack on the sample obtained from the in-service plate. Figure 4 and 5 shows the parameters obtained from the roughness and waviness measurements taken along the bulk of the sample as shown by the extracted profile. The skewness, $R_{sk}$, is indicative of the sample consisting of many valleys or pits since it is a negative value. Furthermore, the arithmetic average roughness, $R_a$, was obtained to be 0.775 $\mu$m.
3.2 Microscopical examination

The microstructures of the plate that corroded in service is shown in figure 6 below. The general microstructure of plate was ferritic as expected from the 10.5 - 12.5 percentage chromium stainless steel.

Figure 2. Contour profile of sample showing different heights.

Figure 3. 3-D surface profile as obtained from confocal laser microscope.

Figure 4. Extracted profile showing lines along which measurements were taken.

Figure 5. Longitudinal profile showing measurements taken along the extracted profile showing length and depth.

Figure 6. The microstructure of the in-service plate showing fine ferritic grains.
3.3 **Chemical properties**

The chemical analysis results of the plate are tabulated in Table 1 below. The sample had a chromium content of 11.3 per cent, this indicated that the corroded plate was indeed a 10.5 – 12.5 per cent chromium ferritic stainless steel.

| Element | Composition (%) |
|---------|-----------------|
| C       | 0.012           |
| Si      | 0.521           |
| Mn      | 0.782           |
| P       | 0.032           |
| S       | 0.008           |
| Cr      | 11.33           |
| Ni      | 0.685           |
| Ti      | 0.203           |
| N       | 0.010           |

3.4 **X-ray diffraction analysis**

The test sample from the in-service wagon plate was subjected to x-ray diffraction analysis to determine the crystallographic structure and the phases of the material. The XRD test results indicated the sample consisted of a significant amount of BCC iron phase, titanium carbides and chromium carbide phases, as shown in figure 7 below.

4. **Experimental Results**

Figure 8 and 9 shows the plates in the as-received conditions from the stores. It was observed that plate B had red rust on the surface even before being put in service.
4.1 Chemical properties

The chemical analysis of the two plates is shown in table 1. The test results had shown that the chemistry of the plates was comparable, however, the nitrogen content of plate A was much higher than that of plate B.

Table 2. The chemical composition of the plate A and B.

| %Elements | Plate A | Plate B |
|-----------|---------|---------|
| Carbon    | 0.039   | 0.016   |
| Silicon   | 0.956   | 0.800   |
| Manganese | 1.034   | 0.870   |
| Phosphorus| 0.031   | 0.024   |
| Sulphur   | 0.0023  | 0.0005  |
| Chromium  | 11.04   | 11.25   |
| Nickel    | 0.714   | 0.743   |
| Titanium  | 0.313   | 0.217   |
| Nitrogen  | 0.320   | 0.010   |

4.2 Microscopical examination

The general microstructure of both plates was ferritic as shown in figure 10 and 11, however, the grains of plate A was observed to be coarser than that of plate B.

![Figure 10](image1.png)  
**Figure 10.** The microstructure of plate A showing a coarse ferritic grains

![Figure 11](image2.png)  
**Figure 11.** The microstructure of plate B showing fine ferritic grains

4.3 Corrosion test results

4.3.1 Exposure Test. Figure 12 and 13 shows the exposure test samples. From the test results, it was clearly evident that plate A has lower corrosion properties compared to the plate B, as plate B was corroding at a much higher rate than plate A. After the test samples were washed and the weight measured, the corrosion rate was calculated to be of an average rate of 0.03735mm/per year for plate B, while plate A corroded at a lower average rate of 0.00965mm/per year.
4.3.2 Salt Spray Test. The sample from plate A did not show any significant corrosion after the salt spray test (see figure 14), however, the sample from plate B showed much more significant corrosion as can be seen by the corrosion products on the surface of the plate B.

4.4 X-ray diffraction analysis
The test samples from plate A and B were subjected to x-ray diffraction analysis after salt spray testing, to determine the crystallographic structure and the phases of the material. The XRD test results indicated that all the three test samples consisted of a significant amount of BCC iron phase, titanium carbides and chromium carbide phases (see figure 16 and 17).
5. Discussions and Conclusions

From the root-cause analysis of the plate sectioned from the in-service coal wagon, it was observed that the plate had a dark grey layer on the surface, this is due to the formation of a thick dark oxide layer which forms during hot rolling of the ferritic stainless-steel sheets [12]. This oxide layer contains depleted chromium layers which render it poor in corrosion properties [13], the layer is usually removed by means of pickling the ferritic stainless steel in inorganic acids such sulphuric and hydrofluoric acid after the rolling and heat treatment processes [12, 14].

It was quite evident that the plate was not pickled after rolling processes as it was showing a red oxide on the after being put in-service for a short period of time. The chemical analysis of the in-service plate had shown that it was a ferritic stainless as the chromium content was 11.33 per cent, whilst the general microstructure was ferritic with fine grains. The surface roughness analysis indicated that there was a presence of pits on the surface of the plate, which was due to pitting corrosion. Pitting corrosion was due to the accumulation of chloride and sulphate ions on the surface of the coal wagon and led to the breaking down of the oxide layer and the initiation of corrosion [8, 9]. The experimental results of the two ferritic stainless steel taken from the stores shown that the two plates had comparable chemistry, however the titanium and nitrogen content of test sample A was slightly higher than that of test sample B.

The microstructures of both test sample A and B were ferritic, however, test sample A showed significantly coarse grains as compared to the more refined microstructure of test sample B. The test sample B consist of low amount of titanium in solid solution as seen from the chemical analysis results, this together with low annealing temperatures of about 880 to 925 degree Celsius, promotes faster recrystallisation of the grains of the material and at the same time promotes the migration of the titanium atoms to the grain boundaries. The titanium atoms then restrict the growth of the grains by the effect of pinning [15]. The XRD analysis results had shown that all the test samples consisted of chromium carbides (Cr7C3), titanium carbides (TiC) and BCC iron phases. Titanium is added to the stainless steel during steel making because of its high affinity for carbon than chromium, therefore it reacts with the carbon in the stainless steel to form TiC thereby preventing the sensitisation effect which is due to the formation of Cr7C3 [11,15]. However, the Cr7C3 carbides cannot be eliminated completely as there is a high amount of chromium in the ferritic stainless steel, hence the presence of small amount of this phase on the XRD results.

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