Effect of putrefied quenching oil on the transformation behaviour of railway spring steel.

V.J. Matjeke¹, G. Mukwevho¹, J.W. van der Merwe²,³,
¹ Transnet Engineering, Research & Development, Private Bag X 528, Kilnerpark, South Africa, 0127
² School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, Private Bag X3, Wits, South Africa, 2050
³ DST-NRF Centre of Excellence in Strong Materials, University of the Witwatersrand, Johannesburg, Private Bag X3, Wits, South Africa, 2050

E-mail: Goodness.Mukwevho@transnet.net

Abstract. Bogie springs are safety critical components that also provide a smooth ride to the rail vehicle by absorbing vibrations and shock loads during the movement of the train. This study investigates the cause of premature failure of springs. These springs were manufactured from a high strength steel grade, SAE J404 grade 5160. The investigation process focused on heat treatment processes and failure mechanisms. Oil properties were also scrutinised by conducting quench tests. The overall findings of the investigation highlighted the detrimental effect of a degraded quenching oil on the fatigue life of the springs. Implementing certain measures from these findings will increase the spring lifespan and contribute towards safe operation of the trains.

1. Introduction
Bogie springs are integral in stabilising and keeping railway fleet on track. They furthermore, give smooth ride to the rail vehicle by absorbing vibrations and shock loads during the movement of the train [1]. In the last century, efforts have been made to produce high performance springs. This is done precisely in an effort to increase the loads and lifespan on the springs. Prominence has been put on improving the strength whilst preserving ductility, toughness and fatigue properties by improving the heat treatment processes and alloy improvement [2].

Premature failures of the springs has been a nightmare for engineers and scientist worldwide since rail inception [3, 4, 5]. The purpose of this study is to investigate primary causes of spring premature failure and evaluation of manufacturing process. The causes of failure of springs are usually due to material, design, manufacturing process and load factors [6]. Generally, springs are designed to withstand cyclic loading over their lifetime. Although the lifetime of the spring is largely determined by loading conditions and outside factors such as corrosion and mechanical damages plays a role in the reduction of lifespan [7]. There are many factors determining the spring life, the service record of the springs in South Africa indicates that generally the springs last for a period of 25 years operating in similar conditions as the failed spring.

2. Background
A spate of helical bogie spring failures has caused grave concern for railway operators in South Africa. The springs are manufactured using hard drawn steel rods that are hot coiled into spring shape followed by heat treatment and shot peening. The springs are normalised and coiled at 850 - 880 °C followed by austenitizing for an hour at 860 - 880 °C and quenching in oil at 40 °C. The quenching
oil properties are summarised in Table 1. The quenching process is then followed by tempering at 430 – 450 °C for 3 hours.

The spring that is investigated is one of the many springs that failed in-service and during the fatigue testing. The spring recorded 203800 cycles before complete failure at a frequency of 3 Hz. The cyclic and mean load were 13.044 and -43.48 kN respectively. The springs are fitted on to the heavy haul locomotives. The required microstructure is tempered martensite with minimum hardness of 50 Rockwell C. The springs are manufactured out of SAE J404 grade 5160 material with the rod diameter ranging from 25 to 35 mm.

Locomotive bogies consist of 12 dual spring sets, i.e. four dual springs per axle. The locomotive carries a maximum load of 22 tons per axle. The load is transmitted directly from the bolster to the subframe to effect compression to the springs. This load is a far less than the spring rated load. Bogie springs are often inspected and monitored for fatigue cracks only during a maintenance intervention cycle due to accessibility difficulties. The intervention period is every four years, during heavy lifting. The first section of this study covers one of the investigation of spring failure that is representative of numerous similar failures, whilst the second part focuses on quenching experimental exercise.

### Table 1. Physical and chemical properties of the quenchant

| Properties       | Value                                      |
|------------------|--------------------------------------------|
| Appearance       | Liquid                                     |
| Flash point      | >204 °C                                    |
| Density          | 0.854 g/cm³                                |
| Pour point       | -15 °C                                     |
| Viscosity        | 20 m²/s @ 40 °C                            |

2.1 Visual examination
The fracture surfaces of the failed spring used in this investigation is shown in Figures 1 and 2. The failure of these springs can be described as fatigue failure that originated on the surface. The failed spring fracture surface in Figure 1 revealed dull area followed by approximately 13 percent fatigue beach marks from the dark area before brittle failure. Figure 2 revealed that the dark dull area which appeared as a pre-existing crack that oxidised during heat treatment. The dark area is identified as the initiation point of the fatigue crack.

![Figure 1. Complete spring fracture surface](image1)

![Figure 2. Cropped image from the point of origin](image2)

2.2 Scanning electron microscope (SEM)
The origin of the fatigue crack was examined by means of scanning electron microscope. The initiation point featured a mixture of transgranular and intergranular cracking typical of quench cracking. The SEM image of the origin of the crack is presented in Figure 3. The surface of the origin...
was covered with what appears to be heat related iron oxide. Oxidation occurred during further heat treatment process (tempering).

**Figure 3.** Failure origin SEM image

### 2.3 Chemical composition

The chemical composition was conducted by means of optical emission spectrometry in element weight percentage. The chemical composition results are presented in Table 2. The composition of the failed spring complied with the requirements of SAE 5160. The steel is classified as hardenable high carbon steel.

**Table 2.** Chemical composition of the failed spring

| Element       | %C  | %Si  | %Mn | %P   | %S   | %Cr  |
|---------------|-----|------|------|------|------|------|
| Failed spring | 0.60| 0.28 | 0.84 | 0.013| 0.004| 0.78 |
| SAE J404 5160 | 0.56-0.64| 0.15-0.35| 0.75-1.00| 0.04 max| 0.03 max| 0.70-0.90 |

### 2.4 Oil quench test

The oil sample that was used to produce the failed springs was collected from the quench tank for quench test analysis. An additional sample of the unused oil was also taken for analysis. The oil samples were taken in separate clean containers for testing. The oil samples were tested using portable quenchant test system (IVF smart quench). The quench tests results are presented in Table 3. Figurative illustrations are shown in Figures 4 and 5. The used oil showed deterioration and as a result had a fast cooling rate at the martensitic start range. The harmonisation of SAE 5160 continuous cooling temperature (CCT) curve shown in Figure 6 and the convection curve shows full martensitic transformation. The CCT curve in Figure 6 was generated using the JMatPro software. The cooling rates of the used oil was severe at critical temperatures of 280 and 300°C.

**Table 3.** Quench test results

| Property                        | Unit  | New oil | Used oil |
|---------------------------------|-------|---------|----------|
| Maximum cooling rate            | °C/s  | 61.6    | 78.9     |
| Temperature at Maximum cooling rate | °C  | 526.0   | 515.9    |
| Temperature at start of boiling | °C  | 619.9   | 615.3    |
| Temperature at start of convection | °C | 331.9   | 240.1    |
| Cooling rate at 300 °C          | °C/s  | 7.3     | 19.0     |
| Time to 600°C                   | s     | 10.9    | 9.8      |
| Time to 400°C                   | s     | 15.8    | 13.1     |
| Time to 300°C                   | s     | 41.3    | 15.1     |
| Time to 200°C                   | s     | 49.8    | 27.2     |
Theta 1 \( ^\circ \text{C} \) 616.3 612.3
Theta 2 \( ^\circ \text{C} \) 398.6 326.3
HP-IVF (Oil) 271.2 756.3

3. Heat treatment experiment
For purposes of validating the earlier discussed findings, hardening experiments were undertaken in order to simulate the heat treatment process. Sample material of SAE 5160 was heated to 860\( ^\circ \text{C} \) and quenched into the new and used oil respectively.

Figure 4. Oil properties cooling rates.
Figure 5. Oil properties convection curves.
Figure 6. SAE 5160 CCT diagram.
3.1 Microscopic examination
The microstructural images are shown in Figures 7 and 8. The used oil microstructure revealed a fully transformed martensite with a crack running through. On the other hand, the microstructure of the new oil reveal matrix of martensite and bainite formations.

3.2 Hardness results
The hardness profile measurements were carried out using micro-Vickers hardness tester. The hardness average and profile results are presented in Table 4 and Figure 9 to 10. The used oil revealed higher hardness when compared to the new oil. The hardness profile was done from one edge to the other, at 1mm interval.

| Quenchant   | Average | Standard deviation | Standard Error |
|-------------|---------|--------------------|----------------|
| New Oil     | 780.9   | 23.3               | 4.6            |
| Used Oil    | 866.8   | 13.9               | 2.8            |

3.3 X-ray diffraction (XRD) results
XRD analysis was conducted on the samples that were quenched with the used oil and new oil. The XRD spectrums are shown in Figure 11, Figure 12. The quantitative analysis showed that the sample quenched with used oil had more martensite transformation than the one quenched with new oil see Table 5. This confirms that the deterioration of oil has an impact on the cooling rates. Filters were used on the diffraction. Phase quantification was conducted using Rietveld.
4. Discussion
The failure of the spring was attributed to the pre-existing cracks that occurred during the production of the springs. The pre-existing crack was positively recognized as quench crack, that developed during the phase transformation. The crack occurred due to uneven rapid cooling of the spring introduced by the degraded oil. The main cause of quench cracks is severe cooling rate and subsequent development of tensile stress on the surface of the spring [8]. The tensile stresses are increased by volumetric martensite expansion during phase transformation. The cracks are often fine on the surface, detectable by dye penetrant testing. The internal stresses that cause cracking can be reduced by selecting a quenchant with slower cooling rates and still promote low martensite transformation [9]. Many researchers have studied the characteristics and behaviour quenchants, however, the effect of the quenching media on specific steels is still lacking [10]. There are numerous grades of quenching oils with different properties and quenching capabilities.

5. Conclusion
The failure of the spring was caused by the existence of a surface quench crack that acted as a precursor for the fatigue crack and subsequent failure. It has been proven that the internal stresses formed can be reduced by selecting quenching media that promote a relatively slow martensite transformation. It is important that the quench oil properties are regularly monitored in order to avoid using degraded oil for quenching operation. Inadequate heat treatment process resulted in deficient microstructures and subsequently poor in-service performance of the springs.

6. Reference
[1] Baek SG, Shin B, Lee SW, Choi YS, Kim J, Koo JC 2013 Optimization of high speed EMU suspension parameters for vibration reduction. J Mech Sci Technol;27:305–11.
[2] Podgornik B, Torkar M, Burja J, Godec M, Senčič B 2015 Improving properties of spring steel through nano-particles alloying. Mater Sci Eng A;638:183–9.
[3] Mukhopadhyay NK, Das SK, Ravikumar B, Ranganath VR, Ghosh Chowdhury S 1997 Premature failure of a leaf spring due to improper materials processing. Eng Fail Anal;4:161–70.
[4] Zhu Y, Wang Y, Huang Y 2014 Failure analysis of a helical compression spring for a heavy vehicle’s suspension system. Case Stud Eng Fail Anal;2:169–73.
[5] Das SK, Mukhopadhyay NK, Kumar BR, Bhattacharya DK 2007 Failure analysis of a...
passenger car coil spring. Eng Fail Anal; 14:158–63.

[6] Pyttel B, Brunner I, Kaiser B, Berger C, Mahendran M 2014 Fatigue behaviour of helical compression springs at a very high number of cycles - Investigation of various influences. Int J Fatigue; 60:101–9.

[7] Artaraz F, Sánchez Beitia S 1991 An unsuitable residual stress state in train springs originated by shot peening. Int J Fatigue; 13:165–8.

[8] Lingamanaik SN, Chen BK 2014 Microstructural and thermo-mechanical analysis of quench cracking during the production of bainitic-martensitic railway wheels. Eng Fail Anal; 40:25–32.

[9] Ravi Kumar B, Bhattacharya DK, Das SK, Chowdhury SG 2000 Premature fatigue failure of a spring due to quench cracks. Eng Fail Anal; 7:377–84.

[10] Chen N, Han L, Zhang W et al. Enhancing mechanical properties and avoiding cracks by simulation of quenching connecting rods. Mater Lett 2007; 61:3021–4.