THERMAL DETERIORATION OF RAILWAY WHEEL STEELS

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ABSTRACT

In the current work the deterioration of mechanical properties of railway wheel steels is in focus. These are commonly made from medium carbon steels (~0.55 wt.% C) heat treated to a near pearlitic microstructure with some 5–10% pro-eutectoid ferrite. The two steel grades studied here are very common on trains in Europe: the R7T grade is mainly used for freight trains and the R8T grade is mostly used for motorized passenger trains. During operation of trains, high thermal loads are evolved because of recurring acceleration, braking, curving and occasional slippage. It is thus relevant to examine the high temperature performance of wheel material and evaluate the decrease in strength after thermal exposure as well as the degradation of fatigue properties. Samples were extracted from virgin wheels and pre-strained to around 6.5% strain, to also account for the change in properties that is induced by plastic deformation inherent in the wheel tread surface. Both un-deformed and pre-strained material was heat treated for different times in the temperature range of interest, from 250°C to 700°C. Hardening was observed in both conditions around 300°C followed by softening at higher temperatures. Spheroidization of the pearlite started to become visible at 450°C for the un-deformed material and at around 400°C for the pre-strained.

1. INTRODUCTION

Medium carbon steels with around 0.55 wt.% carbon are commonly used for the manufacturing of forged railway wheels because they combine good strength and wear properties. After forging, the wheels are heat treated to a microstructure consisting of mostly pearlite with some 5-10 vol. % pro-eutectoid ferrite just below the wheel tread (Cvetkovski, Ahlström and Karlsson 2011). Two grades are very common on trains in Europe; the R7T grade is the dominating grade on freight trains and on many passenger coaches, while the R8T grade with slightly higher carbon content is often used for passenger trains with driven wheels, so called EMUs (Electric multiple units) (Mädler and Bannasch 2014). During train operation, high thermal loads are evolved because of recurring acceleration, braking and curving. Literature investigations showed that the temperature in the wheel tread can rise up to 550°C during freight operation with some extreme cases going up to 800°C (Carsten and Eifler 2009). The influence of thermal loadings up to 750°C will be in focus in the current investigation. Even higher temperatures up to approximately 1050°C can be reached on occasional slippage when the wheels skid along the rail for a short time (Ahlström and Karlsson 1999a; Ahlström and Karlsson 1999b). This causes phase transformations in the steel, often resulting in brittle martensitic patches on the wheel tread that can lead to spalling and other problems; however this case is outside the scope of the current investigation. Apart from thermal loadings, plastic deformation in the tread surface changes the material microstructure and leads to an increased sensitivity to thermal damage. Control of material property degradation in wheels is an important topic for guiding maintenance and ensuring safety of railways.

At exposure to medium temperatures, starting from around 400°C up to around 750°C, an increasing microstructural degeneration occurs. Since the initial microstructure is predominantly pearlitic, the strength and wear properties of the material depend mainly on the interlamellar spacing of the pearlite (Modi, Deshmukh, Mondal, Jha, Yegneswaran and Khaira 2001; Clayton and Danks 1990). It is known that exposure to elevated temperatures yields spheroidisation of the pearlitic structure, which makes it softer (Cvetkovski, Ahlström and Karlsson 2011). After the material has experienced plastic deformation, the material becomes even more prone to spheroidization of the lamellas on exposure to high temperatures (Cvetkovski, Ahlström and Karlsson 2011; Chattopadhyay and Sellars 1982; Arruabarena, Uranga, Lopez and Rodrigues-Ibabez 2011; Cvetkovski and Ahlström 2013]. It is thus necessary to understand the influence of combined deformation and heating on the microstructure and how this in turn affects the mechanical properties of the material.

Previous investigations have showed a cyclic hardening at 300°C and cyclic softening at higher temperatures in virgin materials R7T (Carsten and Eifler 2009; Ahlström 2013). The results on cyclic behaviour of R7T are repeated here as this information is not readily available (Ahlström 2013). The change in room temperature (RT) hardness after exposure to elevated temperatures between 500°C up to 725°C was also studied before for the R8T grade (Cvetkovski, Ahlström and Karlsson 2011).

The aim of the present study is to investigate the changes in properties that are induced by thermal degradation without and with prior plastic deformation. Specifically, the change in room temperature (RT) hardness after exposure to elevated temperature from 250°C up to 450°C of R8T originally in its virgin state is examined to complement the results of previous studies (Carsten and Eifler 2009; Köppen, Karlsson and Ahlström 2006]. It also aims at presenting the change in RT hardness after exposure to elevated temperatures of 250 to 700°C after pre-straining to 6.5% plastic strain. This will account for plastic deformation that is induced during operation and will thus lead to a better understanding of the importance of this parameter for the change in material properties.

2. EXPERIMENTAL

2.1 Material

The steels studied in the present work were the R8T and the R7T wheel steel grades. These materials follow the standard EN13262 (European committee for standardization 2009) and their nominal compositions are shown in Table 1. Within the standard, the materials are called ER8 and ER7 respectively but here the commonly used names R8T and R7T will be used. The "T" added to the designation marks that the wheels have been rim chilled (the tread and flange are cooled with water jets) during production. This creates a fine-pearlitic microstructure close to the rim with a slight decrease in hardness and a slight increase in free ferrite with increasing depth, see for example (Cvetkovski, Ahlström and Karlsson 2011; Ahlström 2013; Ahlström 1999a; Lunden and Paulson 2009).

Table 1 Chemical composition of R8T and R7T wheel material, maximum levels, in wt%

	C	Si	Mn	Mo	Cr	Ni	S	P	V	Fe
R8T	0.56	0.40	0.80	0.08	0.30	0.30	0.015	0.020	0.06	Bal.
R7T	0.52	0.40	0.80	0.08	0.30	0.30	0.015	0.020	0.06	Bal.

The two materials have similar microstructure but with a slightly higher ferrite content in R7T. Except for higher strength of the R8T material, their mechanical behavior in terms of hardening and fatigue characteristics is similar.

Samples of R8T were extracted from unused wheels from around 15 to 20 mm below the wheel tread surface; this material has a representative microstructure for volumes exposed to elevated temperatures and mechanical loading during operation. The flange and the side closer to the rim face were excluded as they have shown to have a variation in hardness due to different cooling rates experienced in the rim chilling process. Also tensile test bars were extracted from the same depth and used for pre-straining tests.

2.2 Prestraining

Tensile bars with thickness 5 mm and "dog bone" shape (see figure 1, dimensions in mm) were pre-strained using an Instron electro-mechanic tensile machine to 6.5% strain and samples were extracted from these bars. Two extensometers were used to prove an even strain distribution. Tests were run in strain control at a strain rate of 10^{-4} s^{-1}. The extension and cross section in the waist were measured before and after some of the tests to verify pre-straining levels. Samples were taken from the waist and cut into pieces around 5x8x8 mm large, used for hardness testing and heat treatment.

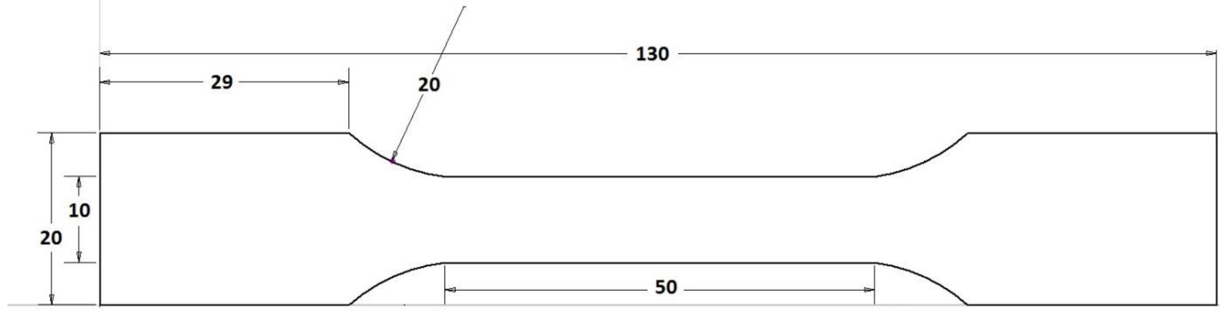

Fig. 1. Pre-strain tensile specimens geometry (in mm).

2.3 Hardness testing and heat treatment

After extraction of samples from un-deformed material and samples from the pre-strained bars, all specimens were ground and polished down to 1 μm diamond suspension before the hardness measurements. Vickers hardness measurements were performed in both virgin and pre-strained material before heat treatment using an applied load of 10 kg. Then the samples were put in a tube furnace with a nitrogen inert atmosphere to prevent oxidation and decarburisation. Both virgin and pre-strained samples were put for 4, 28 and 238 minutes at temperature range of 250–700°C. After heat treatments at selected times and temperatures, new room temperature hardness measurements were performed. The indentations were made randomly on the specimen surface at a distance more than twice the diagonal length of the previous indentation. The hardness was taken as the mean value of three indentations, as measured on the screen of the hardness tester (Wolpert 2RC). For the un-deformed material, heat treatments were performed only up to 450°C since temperatures above that level were studied in a previous work (Cvetkovski, Ahlström and Karlsson 2011).

2.4 Low cycle fatigue testing

The low cycle fatigue characterization from the previous study (Ahlström 2013) is briefly repeated here. The tests were performed on R7T material using cylindrical tensile test bars and an Instron servo-hydraulic test frame. Samples with gauge diameter 6 mm were taken out from the wheel rims at a depth of approximately 15 mm below the running surface. Low cycle fatigue tests were run in strain amplitude control with triangular wave shape at R_{ε} = -1 and strain rate $5 \cdot 10^{-3}$ s^{-1}at constant total strain amplitude 0.6 %. Peak/trough values were recorded for every cycle, and full hysteresis loops were recorded for the initial 25 cycles and thereafter regularly during the whole lifetime. The machine was equipped with a furnace to perform tests at elevated temperatures of 300^{o}C and 500^{o}C. Also tests with 0.4% and 1.0% strain and tests with hold time were done, but here only the 0.6% strain amplitude tests are presented.

2.5 Microstructural evaluation

Light optical microscopy (OM) and scanning electron microscopy (SEM) were used to evaluate the initial and final microstructures. Samples were mechanically ground and polished to 0.04 μm for the OM and SEM evaluations. Etching was done using Nital (3% HNO_3 in ethanol).

3. RESULTS AND DISCUSSION

3.1 Hardness

The initial hardness value for the virgin, also called “undeformed” R8T material is around 256 HV10 and around 274 HV10 for the prestrained condition. The effect of the heat treatments is shown in Fig. 2. It is clear that a hardening process is taking place around 300°C similar to what was previously observed from cyclic hardening experiments, see below (Ahlström 2013). For both the virgin and the pre-strained material it seems that this hardening is more pronounced when the material is subjected to 28 min heat treatments. At temperatures above 350°C, softening occurs for all three time durations. For the temperature range 400-450°C, both conditions have lost a few percent in hardness.

There is some scatter in the hardness data which partly is caused by limitations in resolution when measuring on the screen of the hardness tester. A future possibility to reduce the scatter is to measure at higher magnification in a microscope.

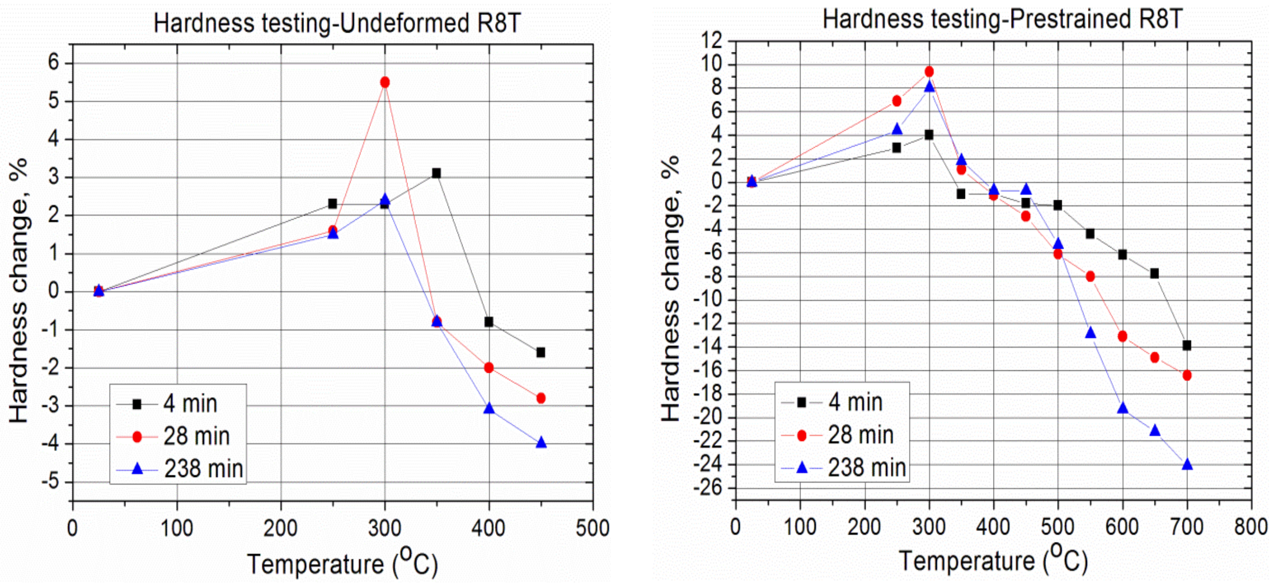

Fig. 2. Hardness change after heat treatments of R8T material.

The decrease in hardness for the pre-strained material reaches almost 25% at 700°C when the samples are exposed for 238 min whereas it is around 14% and 16% for 4 and 28 min respectively. The above results indicate that plastic deformation combined with exposure to high temperatures for example after excessive braking in train operation will have a great impact on the material mechanical properties.

3.2 Low cycle fatigue properties

The cyclic behaviour of the R7T material at room temperature (20°C) and elevated temperatures is shown in Fig. 3. Fatigue test results for R8T at 20°C (from Köppen et al. 2006) are also drawn for comparison and they prove the similar behaviour between the two materials, with the only difference being the strength level. At 20°C both materials exhibit an initial softening, and then a slight hardening during the main part of the fatigue life. At 300°C hardening starts rather strongly, and then continues further on but with a decreased rate. At 500°C instead softening can be observed during the entire fatigue life. Approximate Young's moduli are determined from every test's first cycle: $E_{(T=20°C)}$= 208 GPa, $E_{(T=300°C)}$= 144 GPa, $E_{(T=500°C)}$= 123 GPa.

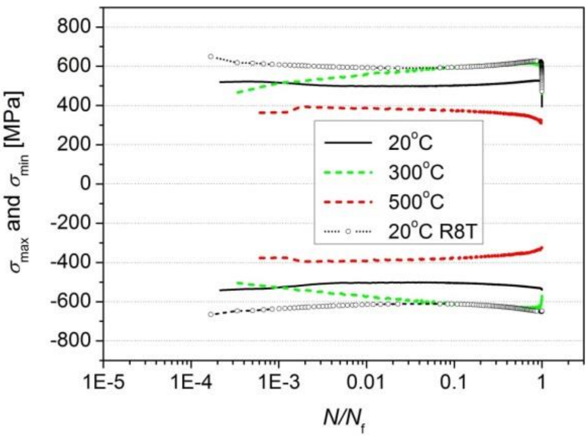

Fig. 3. Development of peak tensile and compressive stresses.

3.3 Microstructure

The initial microstructure consists of pearlite (dark areas in Fig 4a, b) and some pro-eutectoid ferrite (white in Fig. 4a, b). The interlamellar spacing was calculated using the method proposed by Vander Voort (Voort and Roosz 1984) using SEM micrographs (Fig 4c, d) and was found to be around 0.12 μm.

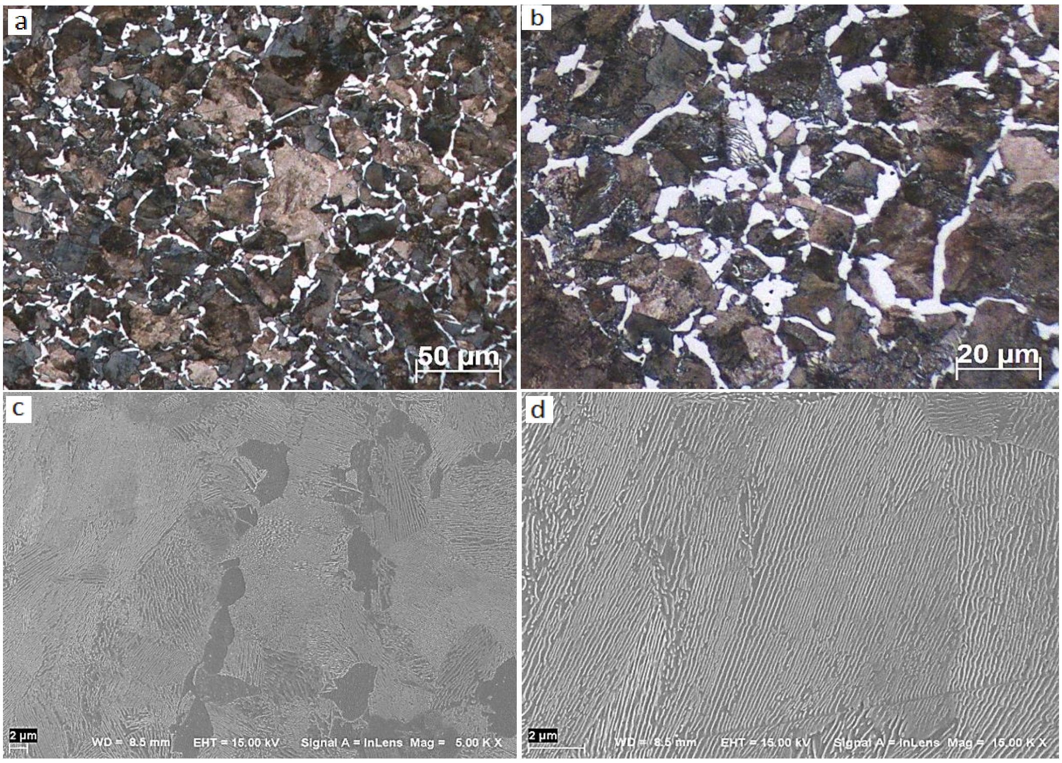

Fig. 4. Microstructural overview of the undeformed R8T using optical microscopy (a, b) and SEM (c, d) at different magnifications.

SEM investigation of the undeformed material, after the annealing treatments, showed that the pearlite lamellas start to break up around 450°C (Fig 5). This effect is more pronounced when the material was held at that temperature for 238 min (Fig 5b). This could explain the small drop in hardness as well.

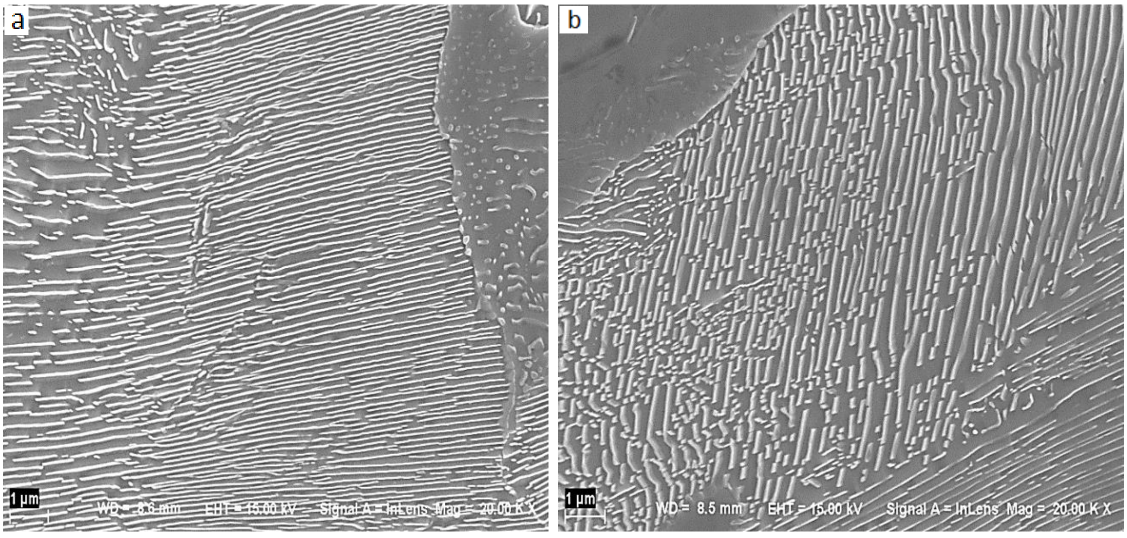

Fig. 5. SEM micrographs of the undeformed R8T at 450°C for 28 min(a) and 238 min(b).

Fig 6 shows the pre-strained R8T after 28 min in four different temperatures (namely 400°C (6a), 500°C (6b), 600°C (6c), 700°C (6d)). It is clear that the pearlite lamellas start to break up earlier than the undeformed material at around 400°C. At 500°C, spheroidization starts to become visible, and the degree of spheroidization increases with higher temperature.

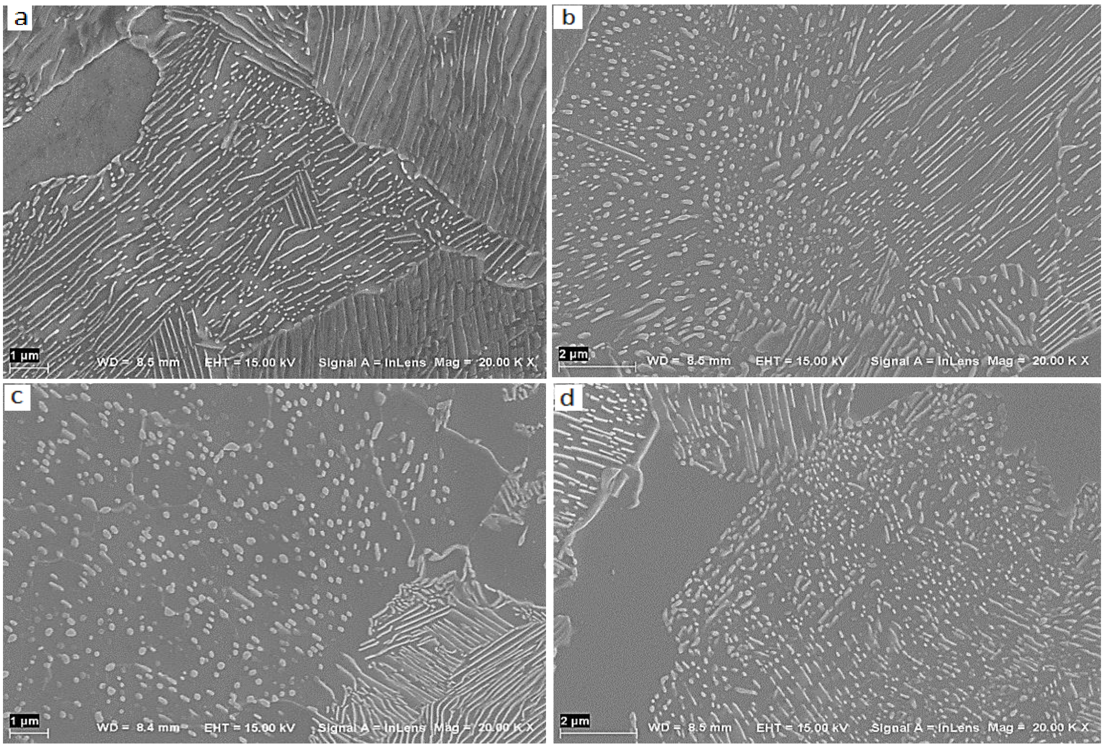

Fig. 6. SEM micrographs of the pre-strained R8T at 400°C (a), 500°C (b), 600°C (c), 700°C (d) for 28 min. hold time.

SEM images (Fig 7) for 238 min. hold time at similar temperatures as before show that at 400–500°C there appears to be a similar degree of spheroidization that is also appearing on the hardness measurements. At higher temperatures, longer time allows for stronger spheroidization which leads to the rapid drop in hardness. One thing that was observed in the pre-strained samples was that due to local plastic deformation different areas showed different degree of spheroidization than others and some pearlite colonies were almost intact even at the higher temperatures. On Fig 7d, the free ferrite content was observed to be higher than the other samples so there is a possibility here that most of the deformation occurred in the ferrite regions thus making it difficult to find fully spheroidized regions.

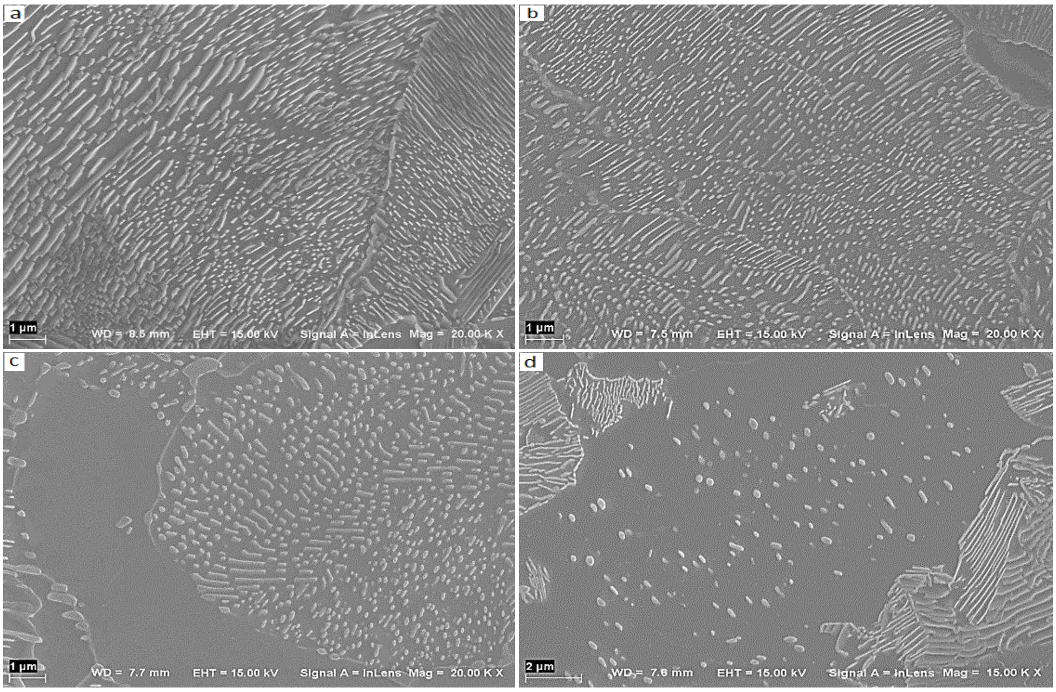

Fig. 7. SEM micrographs of the pre-strained R8T at 400°C (a), 500°C (b), 600°C (c), 700°C (d) for 238 min hold time.

4. CONCLUSIONS

The effect of thermal loading on the mechanical behavior of two railway wheel steels was evaluated. The two materials R8T and R7T exhibit a slight difference in carbon content and thus a slight difference in hardness but otherwise behave similarly. Annealing treatments of R8T and evaluation of cyclic mechanical properties of R7T allowed for the following conclusions.

1. The hardness increase around 300°C is evident for both un-deformed and pre-strained conditions. It is more pronounced in the pre-strained material.
2. Above 350°C softening occurs. Decrease in hardness at 500°C was around 5% for both conditions, and reached almost 25% at 700°C for the pre-strained material.
3. Hardening was also observed during the low cycle fatigue tests for 300°C. Cyclic hardening starts rather strongly in the beginning of the fatigue life and then continues with a decreased rate. At 500°C, cyclic softening can be observed during the entire fatigue life.
4. Pearlite lamellas for the un-deformed material start to break up around 450°C. More pronounced effect for longer hold times.
5. Pearlite lamellas start to break up earlier for the pre-strained material at around 400°C. Deformation appears to be local so some regions remain unaffected by temperature.
6. Spheroidization of pearlite strongly influences mechanical properties with a significant decrease in hardness.

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