Crack initiation caused by repeated local heating events – Modelling of possible mechanisms

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ABSTRACT

Thermally initiated damage mechanisms by short-term local surface heating of a rail or wheel have been examined. A Finite Element (FE) model incorporating phase transformation from near pearlitic steel to austenite, and then to martensite was built to examine developing strength and residual stress fields. The FE model also incorporates thermal contraction on tempering of the martensite by following heat pulses. The material is modeled as isotropic, but with properties varying with phase, temperature and tempering state. Different thermal sequences that could cause crack initiation are examined.

Keywords: Finite element model, fatigue crack initiation, squat, stud, RCF crack cluster, thermal damage, phase transformation, martensite, residual stress

1. INTRODUCTION

It is an important technical task to minimize damage in railway wheels and rails. This is often challenging since there are not always evident relations between loadings and generated damage. From the experimental side, the problem is often addressed by investigating samples from field. But any wheel or rail sample that has been in service, has experienced different combinations of mechanical and thermal loadings and loading histories during its life, and often the documentation of loads is not available at all or limited. This makes the analysis difficult and the actual loading sequences that caused the damage are not readily determined. Theoretical analyses often attack the problem from the other direction, using idealized loading cases, with the purpose to examine if the loading case modelled could be a possible explanation for damage observed in field.

This study is mainly theoretical and aims at investigating if thermal loadings, imitating repeated local friction heating in a railway wheel-rail contact surface, could be a contributing mechanism to crack initiation in wheels and rails. The material descriptions needed for the analyses are built on experimental observations documented in previous works. All results presented in this conference proceedings version of the article, and parts of the descriptive text, are reproduced from a published article with a wider scope [1] with permission from Elsevier.

The big picture of the problem at hand is given in this paragraph; a more detailed description follows. Railway wheels and rails are commonly made from medium carbon pearlitic steels. The temperature reached in operation is sometimes high enough to cause austenite formation in a thin surface layer, which on cooling transforms again – this time to martensite. If repeated heating occurs in the same spot, the surface layer can either re-austenitize or re-order into a tempered martensite state. Thermal expansions and contractions occur as an effect of temperature changes, phase transformations and reordering. Such thermal processes cause both large residual stresses and microstructural changes with associated large gradients in strength and toughness. This, in combination with high stress levels, could potentially lead to initiation of cracks [2-4].

A certain degree of slip is always present in rolling contact. Higher slip occurs due to curving, acceleration or braking and in some cases, for example upon wheel skid which happens when a wheel is
locked for a short period of time, full slip develops. This often leads to frictional heating up to temperatures sufficient for austenitization of a thin surface layer. Due to the increased temperature, the flow stress decreases and thus the magnitude of the stresses are limited. Upon transformation to austenite, new strain-free grains are formed, with very low flow stress at the high temperature. When heating ceases after a relatively short period, the temperature gradient is high. This leads to efficient self-cooling by heat conduction into colder inner parts of the wheel or rail. The in-sufficient time for diffusional transformation causes martensitic transformation in the austenitized material volume. Martensitic transformation from austenite progresses gradually in a relatively low temperature range as temperature is decreased from around 300°C down to room temperature for the type of steels studied here. On repeated heating to temperatures around 100–500°C, the martensite is tempered.

Thermal expansion rates are often quantified using the coefficient of linear thermal expansion (CLTE, K⁻¹). The CLTE is slightly higher in austenite than in ferrite, pearlite and martensite [5] with a slight temperature dependence. Upon martensitic transformation from austenite, the volume increases considerably, around 5% [5]. In a free body that simultaneously transforms from austenite to martensite, this volume expansion can occur without the generation of macroscopic stresses. But, if the austenite is restricted by surrounding material, or if it decomposes sequentially within a body, residual stresses will arise upon martensitic transformation. Also during transformation from austenite to ferrite and pearlite, a volume increase occurs. However, as-quenched, “un-tempered”, martensite has a slightly lower density than pearlite, meaning that when martensite is tempered, a volume decrease takes place due to the reordering of the martensitic α’ (bct) phase to the ferritic α (bcc) phase and carbide.

In the case of railway wheels or rails, where a surface layer is transformed to martensite, the residual stresses will be difficult to predict without good descriptions of material properties. Also, careful simulation of the thermal process is required, as this affects stresses, strength and dilatation. For example, it has previously been shown that during wheel flat formation (when a certain spot on the wheel is heated for a short time), the cooling proceeds faster in the periphery of the transformed “disc”, due to the more divergent heat flow, compared to the center [6]. The gradual transformation to martensite generates other stress fields than what would have been the case if the all austenite transformed simultaneously.

The FE modelling presented in this paper is done to characterize resulting stress and strain fields due to repeated surface heating of a pearlitic steel. The model utilizes temperature and structure dependent material properties, including thermal expansion and flow stress. Specimens were modelled as axisymmetric coins with controlled temperature at the center of the top surface. Using this modelling framework, different thermal loading cases are analyzed, giving rise to different strength and stress fields. The results could be useful for judging possible increased risks for crack initiation during following mechanical loadings. Most of the material descriptions and results are reproduced from published articles [1] with permission from Elsevier. The aim is that this study will extend to include modeling of phase transformation from pearlite via austenite to martensite, with subsequent martensite tempering, however in this conference version of the article, the cases modelled all consider martensitic starting structures (un-tempered or tempered), and the geometry is in the form of a small coin.

2. MODEL

2.1 Material

The mechanical material behaviors for different railway steels have been examined and reported previously [7–10]. Despite slight differences in carbon content and cooling rates during production, the different pearlitic steels exhibit similar behavior regarding monotonic and cyclic hardening, but the strength level naturally differs, mainly depending on carbon content and pearlite lamellar spacing. For the current study, experiments done on fine-pearlitic railway wheel steels (ER7T, ER8T and Sura B82) were used as input for material models.

The mechanical behavior of martensite at different temperatures and at different degrees of tempering, as well as thermal expansion characteristics of pearlite and martensite, were reported and explained in [1]. However, for ease and clarity, the dilatational effects and the drop in room temperature hardness upon tempering are briefly explained below.

The tetragonal (bct) lattice of un-tempered martensite gradually re-orders towards the cubic (bcc) lattice of ferrite as the carbon diffuses out
from the lattice to form carbides. This is evident when studying expansion of martensite upon heating, seen in Figure 1. Because of the re-ordering to ferrite + carbides, the martensite expands less than other constituents. Upon cooling, the partly- or fully-tempered martensite contracts just like pearlite. The difference between these curves quantifies the shrinkage.

Figure 1. Linear thermal expansion on heating and cooling of martensite and pearlite.

Also experiments were done where heating was interrupted at different temperatures before complete reordering, the specimen was brought back to room temperature, and a new heating cycle was started. Then, the behavior followed the pearlite’s slope up to the previous peak temperature, and thereafter continued along the martensite heating curve [1]. For un-tempered martensite that has been brought to a peak temperature of 575°C then back to room temperature, the length decrease is 0.22%, which is in agreement with previous research [5]. Higher temperatures do not cause further deviations as the martensite is then fully reordered to ferrite + carbides.

Thermal expansion and contraction of austenite was taken from literature combined with simulations using JMatPro6.0 software (Sente software).

The strength of martensite drops rapidly upon tempering [1]. To handle the effect of tempering on flow stress, a tempering parameter with values corresponding to the room temperature Vickers hardness, was defined, “HV”. Thus, for each position, the peak temperature so far \( T_{\text{peak}} \) in °C gave the degree of tempering according to the formula: \( HV=810-0.67T_{\text{peak}} \) (rationalization of experimental results). The martensite loses approximately half of its strength on a 0.1 second heating to around 600°C. When modelling the strength of the material at elevated temperature, the degree of tempering was combined with experimental flow stress curves from compression tests, to quantify the flow stress at a certain temperature [1].

2.2 Finite element model

The commercially available software: Abaqus 6.9 Standard by Dassault Systèmes was used for simulations [11]. It has the ability to link user-defined subroutines into the compilation, and thus become very versatile. In the current work, three such user defined subroutines were included. The subroutine HETVAL was used for modeling of phase transformations and latent heat evolved. It was also used to modify variables that affect strength of the material. Thermal expansion was modelled using the subroutine UEXPAN, and parameters submitted from HETVAL were used to enable phase dependent thermal expansion. The heat distribution was modelled using DFLUX.

An axisymmetric mesh with 3000 elements was used, see Figure 2; the element size close to the heated surface \((0 \leq r \leq 3.0 \text{ mm}, y=0 \text{ mm})\) was 0.025 mm thick, 0.075 mm wide. Coupled temperature-displacement analyses were run with four-node bilinear displacement and temperature elements (CAX4T). Each of the 3111 nodes have three degrees of freedom: temperature and displacement in radial and depth directions.

Figure 2. Axisymmetric mesh

The kinetics of phase transformations occurring at constant temperature is often presented in isothermal transformation diagrams (IT-diagrams). These diagrams can also be used to describe phase transformations during arbitrary cooling schedules, assuming additivity of transformed phases. The principle is to subdivide the cooling curve in a number of small isothermal steps. In each step, the transformed fraction is calculated using the Avrami expression, presented in Equation (1). In the equation, \( f \) is the fraction of transformed material, \( t \)
is the time and $b$ and $n$ are temperature dependent constants that can be determined from the IT-diagram.

$$f = 1 - \exp(-bt^n) \quad (1)$$

For ferrite, the exponent has been set to $n = 2$.

The formation of martensite was treated as purely temperature dependent according the Koistinen-Marburger equation [9]

$$f = 1 - \exp(-0.011\cdot(M_S - T)); \quad T \leq M_S \quad (2)$$

The volume fraction $f$ thus depends solely on the undercooling under $M_s$.

Temperature dependent specific heat and thermal conductivity were implemented for the actual chemical composition of the material, based on data from Thermo-Calc (Thermo-Calc software), and reported in earlier publications [6].

2.3 Mechanical properties and dilatation

The elastic response of the material was implemented with slight temperature dependence of the Young’s modulus $E$, decreasing from 210 GPa, at 20°C, down to 150 GPa, at 700°C, according to data from JMatPro6.0 (Sente software) and calculated for the actual chemical composition. The elastic properties were not implemented as phase dependent. The plastic properties of ferrite and pearlite were implemented based on mechanical tests reported in previous works, basically in agreement with standard specifications of the actual materials.

To describe the plastic properties of martensite is more challenging. First, the un-tempered martensite is very brittle. However, thanks to the volume expansion occurring when martensite forms, a compressive stress field gradually builds up in martensite that is restricted from expansion. Thus immediate cracking during martensite formation is less likely and not often observed in A local decrease of tempering parameter value was assumed to give a proportional decrease of local flow stress. An initial hardness of 780 HV was set for the as-quenched (un-tempered) coins, and of 408 HV, corresponding to tempering at 600°C, for the tempered coins. Initially, the coins were assumed to be globally stress-free.

The thermal expansion was modelled using the data from the dilatometry experiments. The comparison between the actual temperature and the peak temperature at each location gave the micro-structural dependence of the thermal expansion, i.e. during the first heating of un-tempered martensite, the primary heating curve was followed, and during cooling and re-heating below the peak temperature of that location, the secondary heating curve, representing tempered martensite, was used. The curve describing un-tempered martensite dilatation was implemented using three polynomials, valid in discrete temperature ranges. The pearlitic, and the tempered martensitic dilatation behavior was well captured using one polynomial, valid within the entire temperature range.

2.4 Computational strategy

An example of the subdivision of the simulations in terms of computational steps is outlined in Table 1.

Table 1. Subdivision of the computation into different computational steps (NB - not time steps, i.e a step can contain several time steps).

<table>
<thead>
<tr>
<th>Step</th>
<th>Boundary conditions and loads</th>
<th>What is simulated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nodes along symmetry y axis fixed in radial direction, bottom node also in y direction. Retained for all following steps.</td>
<td>Insertion of coin into sample holder and temperature stabilization at 100°C.</td>
</tr>
<tr>
<td></td>
<td>Temperature of all nodes increased to 100°C</td>
<td>Thermal expansion of entire coin from 20 to 100°C. (No stresses generated.)</td>
</tr>
<tr>
<td>2</td>
<td>Heat absorption on central part of top surface, otherwise insulated surfaces.</td>
<td>Laser heating. Thermal expansion and arising stress and strain fields.</td>
</tr>
<tr>
<td>3</td>
<td>Heat conduction to sample holder on bottom surface.</td>
<td>Cooling. Thermal contraction and arising stress and strain fields.</td>
</tr>
<tr>
<td>4</td>
<td>Temperature of all nodes decreased to 20°C.</td>
<td>Thermal contraction on cooling to 20°C. Final residual stresses.</td>
</tr>
</tbody>
</table>

The parameter values used for the different cases simulated are seen in Table 2 below.

Table 2. Cases simulated. Approximate peak temperature ($T_{peak}$) and time spent within some 30°C from $T_{peak}$ given.

<table>
<thead>
<tr>
<th>Case</th>
<th>Heating rate</th>
<th>$T_{peak}$ (°C)</th>
<th>Time @ $T_{peak}$ (s)</th>
<th>Starting Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>High</td>
<td>225</td>
<td>2</td>
<td>Un-tempered M, 780 HV</td>
</tr>
<tr>
<td>M2</td>
<td>High</td>
<td>400</td>
<td>2</td>
<td>Un-tempered M, 780 HV</td>
</tr>
<tr>
<td>M3</td>
<td>High</td>
<td>575</td>
<td>2</td>
<td>Un-tempered M, 780 HV</td>
</tr>
<tr>
<td>M4</td>
<td>Low</td>
<td>575</td>
<td>4</td>
<td>Un-tempered M, 780 HV</td>
</tr>
<tr>
<td>M5</td>
<td>Very High</td>
<td>575</td>
<td>0.1</td>
<td>Un-tempered M, 780 HV</td>
</tr>
<tr>
<td>TM3</td>
<td>High</td>
<td>575</td>
<td>2</td>
<td>Tempered (600°C) M, 408 HV</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

This conference paper contains only results from the previous article [1]. The intention is that the presentation and the manuscript for the final paper will contain further cases. The numbering of cases complies with Table 2.

3.1 Un-tempered martensite, cases M1-M5

The radial stress for case M5, the case with the highest temperature gradients, is shown in Figure 3.

![Figure 3](image)

Figure 3. Radial stresses overlaid on the deformed mesh; deformations magnified 50x. (a) Case M5 before cooling. The peak stress is not sufficient to plastically deform the material. (b) Case M3 after cooling to room temperature. Shrinkage due to local martensite tempering is clearly seen. Thickness 3 mm, x-scale=y-scale.

The stress distribution just before cooling ($T_{\text{peak}} \approx 575^\circ\text{C}$) is shown in Figure 3a; the peak stress is approximately -550 MPa. The von Mises stress has approximately the same magnitude, and is not sufficient to plastically deform the material; this is valid in every location and every time step for all of the cases M1 – M5. The radial stress distribution for M3 after final cooling to room temperature is shown in Figure 3b.

3.2 Tempered martensite, cases TM3-TM5

The radial stresses for case TM3 are shown in Figure 4a. The stress in the center reaches 240 MPa, and rapidly drops; only the volume which was plastically deformed during heating shows large tensile stresses, Figure 4b.

![Figure 4](image)

Figure 4. (a) Radial stresses (MPa), and (b) accumulated plastic strain (-) of case TM3 after cooling to room temperature. Deformations magnified 50x. Thickness 3 mm, x-scale=y-scale.

3.3 Stress depth profiles for M1-M5, TM3-TM5

Depth profiles of radial stresses for all cases along the center line after final cooling are shown in Figure 5.

![Figure 5](image)

Figure 5. Radial stresses after cooling to 20°C for all cases in Table 2.

For case M1 stresses are negligible, below 25 MPa. Case M2 shows a maximum radial stress of around 100 MPa, decreasing towards the bottom surface; while case M3 has a more even distribution of residual stresses, as most of the dilatation differences have been exploited through the entire coin thickness (the peak temperature at the center line, towards the bottom of the coin, is around 370°C). Case M4 is more extreme in this respect, and stress levels are lower as a larger part of the coin has decreased its volume (heating the entire coin to the same temperature would give only shrinkage, no residual stresses). M5, on the other hand, shows that the larger temperature gradients
achieved with rapid heating, gives correspondingly larger gradients in residual stresses.

The fact that all cases M1-M5 show somewhat lower stresses at the surface is believed to be due to the increasing degree of plane stress condition, naturally prevailing on a free surface. Stresses were below the yield stress for all locations in M1-M5, thus the strains are caused by volume decrease upon tempering of martensite, and to some degree of warping of the coin. The most obvious difference for the tempered materials (TM3-TM5) is the much shallower residual stress profile. For these cases, no dilatation effects (referring to the anomalies due to reordering) affect the solution. Thus, all residual stresses developing are due to the plastic deformations caused by the thermal strain with respect to the flow stresses. Plastic deformation in compression occurs in the heated volume at high temperature, giving rise to residual tensile stresses after cooling. However, to reach the yield stress, a certain thermal strain gradient is needed, while lower heating rates will render less, or no, residual stresses.

4. DISCUSSION

The FE analysis showed that residual stresses are attainable by local heating of both as-quenched and tempered martensite, but are governed by different mechanisms. The development of residual stresses depends on heating rate, peak temperature, and mainly two material properties: thermal expansion/contraction and yield strength. For the case of as-quenched martensite (cases M1-M5), the low thermal expansion and high yield strength caused no plastic deformation to take place during the heating stage for all studied cases. However, residual stresses were instead obtained by local volume decrease. The amount of shrinkage is a function of the peak temperature, which is analogous to reaching higher on the curve in Figure 1. As long as the heated volume is surrounded by non-affected material, essentially tensile residual stresses are present. Heating rate and time at peak temperature have no profound effects; these factors only affected the temperature field and affected volume, in accordance with the experimental data [1]. In contrast, the magnitude of residual stresses in pre-tempered martensite (cases TM3-TM5) shows a strong dependence on heating rate and peak temperature. While there is no shrinkage effect after heating, the thermal expansion is larger for the tempered martensite and the yield strength is lower. For high heating rates, plastic deformation in compression of the heated clamped volume results in residual stresses after cooling with large stress gradients. Tensile stresses are present in a thin surface layer, and compressive stresses below (see Figure 5). There is a distinct limit in heating rate below which no residual stresses will form. The reasoning regarding tempered martensite is also valid for local heating of pearlitic material. With its generally lower flow strength, compared to tempered martensite, and almost identical thermal expansion, pearlite is even more prone to residual stress formation by plastic deformation of the surface. Also for as-quenched martensite, plastic deformation of the locally heated volume may occur, but it requires an even larger gradient in thermal strain, due to the lower thermal expansion. Thus a combination of the two, principally different, processes can occur for extremely rapid heating to sufficiently high temperatures.

An isotropic plasticity model is not optimal for medium carbon steel, but proved sufficient for evaluating the principal behavior in the cases studied. In the as-quenched martensite, no plastic deformation occurred and thus only the elastic part of the material model was utilized. For the tempered martensite, a lower flow stress was present from the start, and it was further lowered by the temperature dependence. For the current cases, the plastic deformation was limited, leading to rather low stresses after cooling, compared to the flow stress. In cases where the flow stress in tension (after deformation in compression) is exceeded, an accurate prediction of residual stresses would require a kinematic hardening model to be used.

Figure 6 shows a longitudinal cross section through a railway wheel that has been skidding along the rail repeatedly.

![Cross section through railway wheel flat, with friction heated layers. The darker grey area in the bottom of the picture represents the un-affected pearlitic base material. The top surface has been heated by skidding](image-url)
against the rail repeatedly. First skid yielded the thickest austenite/martensite layer, and following skids have re-austenitized and tempered the previous layers. From [3].

The first skidding event has caused austenitisation to a depth of some 1.2 mm, and martensite has formed upon cooling. The second skidding event re-austenitized the thin surface layer, but the temperature field at larger depths has tempered the martensite formed in the first skidding event. According to the current work, this should yield tensile stresses in the primary martensite. The crack seen has formed in the tempered martensite, having an increased stress level. It seems probable that the tensile stress generated on martensite tempering has contributed to the cracking. A third skidding event has partly tempered the secondary martensite layer.

5. CONCLUSIONS

Residual stresses arising on local heating, with subsequent cooling to room temperature, have been evaluated using finite element analysis for as-quenched and tempered martensite.

Finite element modelling showed residual stresses develop in as-quenched martensite, solely by the effect of volume decrease associated with tempering after local heating, and independent of heating rate. Thus, any local temperature increase in the material gives residual stresses after cooling. For the case of tempered martensite, the residual stress field instead depends on the heating rate and peak temperature, giving sufficiently large thermal strain gradients to cause local plastic deformation. This results in a large stress gradient, with tensile stress in the surface, and compressive stress below. This is in contrast to as-quenched martensite, which exhibits a broad tensile residual stress distribution around the whole tempered volume.

6. ACKNOWLEDGMENTS

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7. REFERENCES