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Low cycle fatigue and deformation behaviour of austenitic manganese steel in rolled and in as-cast conditions

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Abstract

This paper presents a characterisation of two austenitic manganese (~12-13 wt%) rail steels, one in rolled (Mn13(R)) and the other in as-cast (Mn13(C)) condition. Cyclic and monotonic behaviour as well as hardness and microstructure have been investigated. The results do not show any major difference between the materials, but comparison with literature reveals large differences compared to pearlitic and bainitic rail steels. The manganese steels are softer initially and harden during cyclic and monotonic loading. © 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Austenitic manganese steel; TWIP steel; low cycle fatigue; deformation behaviour; railway rail steel.

1. Introduction

Austenitic steels have been investigated in terms of tensile strength and fracture toughness for example for automotive applications in previous studies. Cost effective manufacturing as well as reduced weight in many applications have increased the interest for austenitic manganese steels [1]. This kind of steel is also used for railway switches or parts of switches. This is due to their higher impact toughness compared to steels used for rails in general [2]. In comparison to other fields of service, low cycle fatigue (LCF) properties are of large interest in railway operation. This is due to high dynamic loads that occur in switches and crossings during train passages. Further, the material parameters identified through LCF testing are used for calibration of material models for numerical computations in switch design.

As-cast austenitic manganese steel (Mn13(C)) has been investigated within the Chalmers Railway Mechanics research centre, CHARMEC and rolled manganese austenitic steel (Mn13(R)) has been investigated as a part of Innotrack [3]. Results from both investigations will be presented and compared in this paper. Both steels have been supplied by the Austrian turnout and crossing manufacturer VAE GmbH.
2. Experimental details

2.1. Materials

Both examined materials are austenitic steels with 12-13 wt% manganese, annealed and quenched in the last production step. One is in as-cast while the other is in rolled condition. Mn13(C) is used in the crossing nose area, while Mn13(R) is used for rails attached to crossings and switches. As can be seen in Fig. 1 the grain size of the Mn13(R) steel is larger than in the Mn13(C) steel. It can also be seen that the cast material contains pores.

The samples of the rolled manganese steel were taken from an actual rail produced for track usage. The samples were extracted a few mm from the rolling surface by electric discharge machining.

Table 1 Approximate chemical composition of the Mn13(R) steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
<td>0.4</td>
<td>12</td>
<td>86</td>
</tr>
</tbody>
</table>

The hardness of the Mn13(R) steel varies greatly over the cross section from as low as 340HV up to 480HV (HV30). This variation was also seen when measuring hardness of the test samples. It is not mainly a difference between different parts of the rail head, but a local variation with a wavelength in the order of 1 mm. This means that in each individual test bar not too big a variation is expected due to global averaging.

Fig. 1. Micrographs of as-cast manganese steel Mn13(C) (left) and rolled manganese steel Mn13(R) (right)

Fig. 2. Hardness distribution over a cross-section of the Mn13(R) rail
For the Mn13(C), special plates were cast for specimen production as it would be difficult to extract representative samples from the actual components. These were cast to reach a similar microstructure and grain size as in the most stressed parts of real components. The approximate chemical composition is given in Table 2.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in wt.%)</td>
<td>1</td>
<td>0.5</td>
<td>13</td>
<td>85</td>
</tr>
</tbody>
</table>

2.2. Mechanical testing and sample preparation

Low cycle fatigue tests were carried out at three levels of constant total strain amplitude $\Delta \varepsilon/2$ (0.4, 0.6 and 0.8/1.0%) and at constant stress amplitude, using saw-tooth wave shape with a constant strain rate of $10^{-2}$ s$^{-1}$. Additional tests with a mean stress were conducted at $R=-0.8$. All fatigue tests were performed at room temperature (+20°C). The test bars were produced according to Fig. 3, and the surfaces were ground and hand polished in several steps to mirror-like finish. Monotonic tensile testing was performed with a strain rate of $10^{-4}$ s$^{-1}$ at three different temperatures (+100 °C, +20 °C, -60 °C).

![Fig. 3. Fatigue and tensile test bar (one grip was kept longer to allow cutting pieces for hardness measurements etc)](image)

All micrographs shown in this paper were taken with light optical microscope. The samples were ground and polished and subsequently etched with Nital (3%).

3. Results and discussion

3.1. Fatigue behaviour

The development of the stress amplitudes during fatigue tests run at two different constant strain amplitudes can be seen in Fig. 4. Both materials behave similarly. The lifetime for the 0.4% strain amplitude tests can be divided into three parts. First the steels show pronounced hardening. The hardening takes place for only a few percent of the fatigue life. Subsequently the materials soften moderately. During the last and longest part of the tests the stress response amplitude is stable. For the 0.6% strain amplitude tests there is no stable part, but softening continues throughout the lifetime. It can be seen that the stress amplitude is somewhat lower for Mn13(C) compared to Mn13(R). The difference in stress amplitude for the two Mn13(R) test samples at 0.4% strain amplitude can possibly be explained by the hardness differences in the virgin material, leading to a higher initial hardness for one
sample than for the other. There was a larger scatter in lifetime for the Mn13(C) materials’ samples which can be explained by the porosity present in the cast Mn13(C) material (Figure 1). It is interesting to note that some of the Mn13(C) specimens survived as long as Mn13(R) ones despite the inherent porosity. This is due to the good ductility of this type of steels, resulting in low defect sensitivity.

Hamada et al. [4] observed a connection between grain size and fatigue life, where fatigue life increased with decreasing grain size. That study was made in the high cycle fatigue area, but similar effects could be expected for low cycle fatigue. No effect like that could be seen in this study probably owing to the porosity of the Mn13(C) material which counteracts the advantage of the smaller grain sizes because of the larger number of crack initiation sites.
like pearlitic and bainitic types [3, 5]. Those materials behave fairly similar under stress and strain loading. If a mean stress is applied the elongation per cycle is constant for most of the life time and increases towards the end.

Fig. 6 shows micrographs of the Mn13(R) steel after deformation. After fatigue testing there was no phase transformation to martensite visible on micrographs. Slip bands are clearly shown on both micrographs.

3.2. Monotonic deformation behaviour

In monotonic deformation none of the tested materials showed any pronounced necking. A general area reduction can be observed leading to the conclusion that repeated local necking and work hardening around the necks take place [6]. For the Mn13(C) the elongation to rupture was somewhat lesser than for the Mn13(R), see Fig. 7. The yield strength and ultimate tensile strengths however, are at a similar level. As a consequence of the smaller grain sizes the work hardening rate is larger for the Mn13(C) material. This is expected according to literature [7].

Planar glide is the dominant deformation mechanism in these materials, both in monotonic and cyclic deformation (Figure 6), but also other contributing hardening factors have been suggested for this type of materials: martensite transformation and twinning. According to Schramm, the stacking fault energy (SFE) for steels like the ones under investigation here is $21 \text{(mJ/m}^2\text{)}$ [8]. For TWIP steels with low levels of carbon (<500ppm), with $\gamma_{\text{fcc}} > 20$
mJ/m² twinning is reported to be a major hardening factor [1]. Preliminary calculations of stacking fault energy for the materials investigated here have been done with JMatPro, software for thermodynamic calculations (see www.sentesoftware.co.uk). The results show considerably higher values at room temperature for the present materials, but more work is needed to confirm this. The high carbon content in these materials stabilises austenite and thus prevents martensite formation. This is confirmed by the fact that no martensite was found in strained material, even after tensile testing at low temperature (-60°C).

4. Conclusions

Low cycle fatigue and tensile tests have been performed on two austenitic manganese steels, one in rolled (Mn13(R)) condition, the other in as-cast (Mn13(C)) condition. Following conclusions can be drawn:

- Manganese austenitic steels differ in deformation behaviour from other railway rail materials. The difference between rolled and cast material has in this study not proven to be very large.
- The longer life time for the more fine-grained cast material was counteracted by porosity.
- During fatigue loading the materials harden significantly, congruent with the monotonic behaviour.
- Smaller grain sizes in the cast material led to larger work hardening rate during monotonic straining.
- Material deformed during tensile testing shows no martensite even after low temperature (-60°C) straining.

Acknowledgements

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References