Low Cycle Fatigue Behaviour of Railway Wheel Steels Including Temperature Effects

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ABSTRACT

This study is focused on fatigue behaviour at low temperatures which is highly relevant for railway operation. It is of course also generally applicable to other components made of medium carbon steels operating at low temperatures. Strain controlled fatigue tests were performed on UIC R8T steel specimens taken from a standard wheel produced by Lucchini Italy. The cylindrical specimens were polished to a mirror finish, completely free from scratches. Tests were carried out at three different levels of total strain amplitude ($\Delta\varepsilon_t/2$): 0.4, 0.6 and 1.0%, at two different temperatures: +20 and –60°C. The results show very little scatter between parallel tests: <1.5% in number of cycles to failure (N_f) at +20°C and <15% at –60°C. It was found that at both test temperatures, after a brief period of initial softening, the material cyclically hardened over the majority of its lifetime at all strain amplitudes. Only a very small flat region, if any at all, was noted, indicating that the dislocation structure was changing constantly over the lifetime of the material. Stress levels were found to be approximately 5 to 15% higher at –60°C, but hardening was slightly less at –60°C. Generally the hardening was more pronounced at high strain amplitudes. The number of cycles to failure was increased at –60°C for $\Delta\varepsilon_t/2$=0.4% and 0.6%, and decreased at 1.0%. Larger scatter in number of cycles to failure was observed at low temperature. This is indicative of the decreased fracture toughness at low temperatures and also of an increased defect sensitivity.

1 INTRODUCTION

It is well known that carbon steels become more brittle at low temperatures. This is substantiated to some extent by the observation that more equipment failures occur in the winter months. However, the understanding of fatigue behaviour at low temperatures is incomplete, and this study is meant to increase the knowledge in this important field.

Earlier studies on the low temperature fatigue properties of steels have indicated some general trends. The long-life constant amplitude behaviour of un-notched samples seems to be better at low temperature than at room temperature. However, with higher loading amplitudes, possibly in combination with notches or inclusions, the room temperature behaviour is better. The more brittle behaviour at lower temperature gives shorter critical crack lengths. There are results that indicate that components that are loaded both at high and low temperature tend to initiate cracks at high temperature when the material is less strong and then propagate the cracks when the temperature is lower [1-3].

2 EXPERIMENTAL

A railway wheel taken from the regular production line of Lucchini Sidermeccanica Italy was used for the experiments. The material used was steel grade UIC R8T where “T” indicates that the rim has been chilled by water spraying, which gives a fine pearlitic structure with some 5% ferrite in the surface zone of the finished wheel. The chemical composition of the current batch is given in table 1. Samples were taken in the tangential direction at a depth of ca 15 mm below the running surface. Five parallel samples were taken from each segment. As a first measurement of scatter in the material properties between samples, hardness measurements were done on both ends of each test bar.

Table 1: Composition of the railway wheel material used in this study in wt.% (Fe-base).

C	S	P	Mn	Cr	Ni	Mo	Cu	Si
0.54	0.006	0.003	0.80	0.13	0.14	0.045	0.14	0.36

Test bars were machined, ground and polished to mirror-like finish completely free from scratches and surface deformation larger than what was caused by the 1 µm diamond paste on soft cloth used in the last polishing step. This was done to ensure that the bulk material properties, and not the surface condition, were determining for the fatigue behaviour of the test bars.

The fatigue testing was done in an Instron 8032 servohydraulic testing machine with electronic control and acquisition at 1kHz, connected to a computer. The machine was equipped with a temperature controlled chamber, cooled with liquid CO_2. Care was taken to prevent moisture from the surrounding air to enter the cabinet.

Tests were run at constant total strain amplitudes of 0.4%, 0.6% and 1.0% at room temperature and at –60°C. All tests were performed at a strain rate of 10^{-2} s^{-1}, except for the first two cycles in all tests which were run at a tenth of this value. Two separate tests were run with identical parameter settings in order to ensure repeatability. In common fatigue testing that number is considered small, but it is evident from the results that it does suffice in this case, owing to selection of material volumes with comparable (and representative) properties, meticulous surface preparations and excellent test control. Failure was defined as when the stress amplitude had decreased to 80% of the value reached in the 24th cycle. For a more detailed description of the experimental methods employed for this study, we refer to Ahlström and Karlsson [4].

3 *RESULTS AND DISCUSSION*

3.1 *Hardness*

There is a general trend that the hardness increases with cross-sectional position away from the flange. For each group of five samples taken from the same segment, the average hardness increases from some 280 HV10 up to 300 HV10. This is plausible if we consider the cooling rate during production. The cooling rate close to the flange is lower as the surface is concave while it is higher towards the edge of the wheel. Between the different segments there was typically a scatter of some 10 units if the same positions were compared. The differences in hardness are thus rather small between different samples, and the same variation was expected for the stress levels in the fatigue testing.

3.2 Fatigue behaviour

In Figure 1, the stress amplitude development for the tests run at 20°C is shown. Each pair of curves develops in the same manner until one crack becomes dominant, i.e. when some 10% of the number of cycles to failure remains (20% for some tests at $\Delta\varepsilon_t/2$=1.0%). Depending on the location where fracture is occurring relative to the extensometer knives, the stresses either increase or decrease rapidly at this stage. However, the portion of the curves affected by this behaviour constitutes to a small part of the total life, and can for most judgements be neglected. During the main part of the life, the difference in stress levels is some 5% for tests done at 1.0% and 0.6% total strain amplitude, and about 2% for tests done at 0.4% total strain amplitude. This difference correlates well with differences in hardness, and can be explained by considering the relative cross-sectional location of the sample when it was taken from the wheel. If we normalise each curve by its respective hardness value (given in the figure), the curves for a given strain amplitude come closely together. The close correspondence between two identical tests until a crack starts to grow is strong evidence that the material is averaging well, i.e. that the cross sectional area is sufficient and that the test is proceeding fine. It is clear that the material softens during the first 10% of its life, and then transitions to a process of slight hardening. The similarity in number of cycles to failure is solid proof of the well defined surface state and cross sections adequatly averaging the microstructure in combination with comparable crack growth rates from the point where one crack becomes dominant.

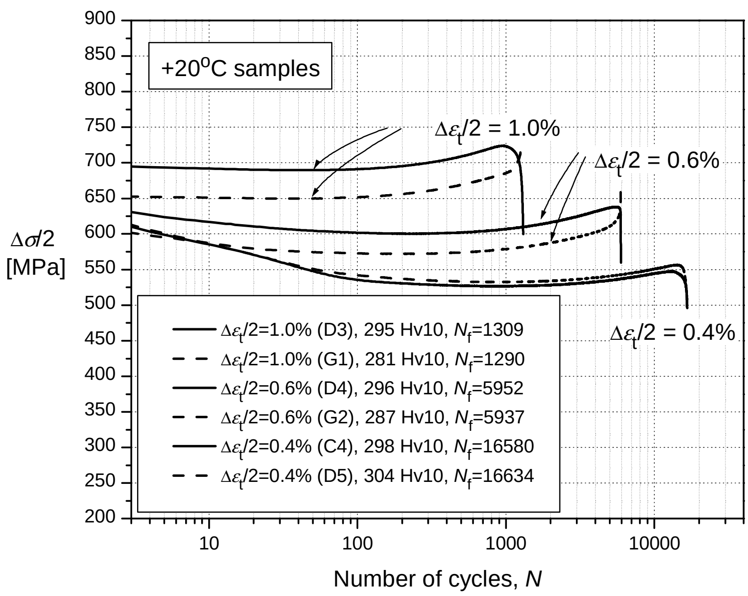

Figure 1: Stress amplitude development for tests run at + 20°C. Numbers within parantheses correspond to sample identification and are in some cases referred to in the text.

In Figure 2, the corresponding curves for the tests run at –60°C are depicted. The stress levels are somewhat higher than at 20°C, in accordance with the monotonic properties [3]. Stress amplitudes are ca 5% higher for tests run at 0.4%, ca 10% higher at 0.6% and 15% higher for tests run at total strain amplitudes of 1.0%. It is noteworthy that, also at this temperature, the material has no stable state but hardens during the majority of its life. Compared to room temperature results, there is a somewhat larger scatter in number of cycles to failure; approximately 5% for tests at 1.0% total strain amplitude, around 10% at 0.6% and ca 15% for tests run at the lowest strain amplitude. The crack growth rate towards the end of the life differs significantly between different tests. One probable explanation for this is that the material is more defect sensitive at low temperature, and when one crack becomes dominant, the local properties adjacent to the crack front have a large influence on the propagation rate.

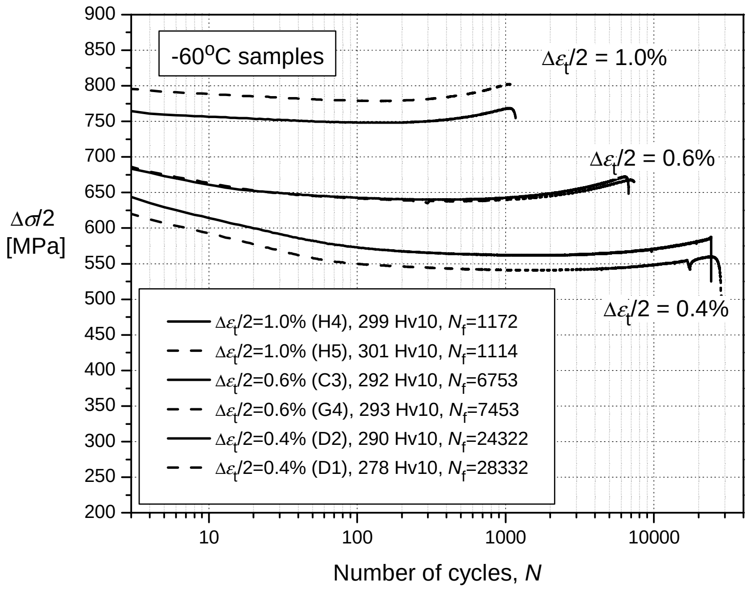

Figure 2: Stress amplitude development for tests run at - 60°C

Figure 3 illustrates the fatigue life at 20°C and at –60°C. The curves derive from the same data as Figures 1 and 2, but here only one sample run at each condition has been selected and a linear scale is used for the cycle number. It is clear that a slight continuous hardening occurs over the majority of the total life for all samples. If it had not been for the loading situation occurring when a crack forms in between the two extensometer knives resulting in decreased loading, the stable development had proceeded longer (cf. samples G1 and G2 in Figure 1). The dip in the curve for sample D1 was caused by a temporary increase in temperature related to a coolant (CO_2) bottle change. During this time, the extensometer heated up leading to decreased stress levels. However, the sample did not increase its temperature notably and, as the stress was never raised above the stabilized level, the incident was deemed not to have any significant influence on the test results.

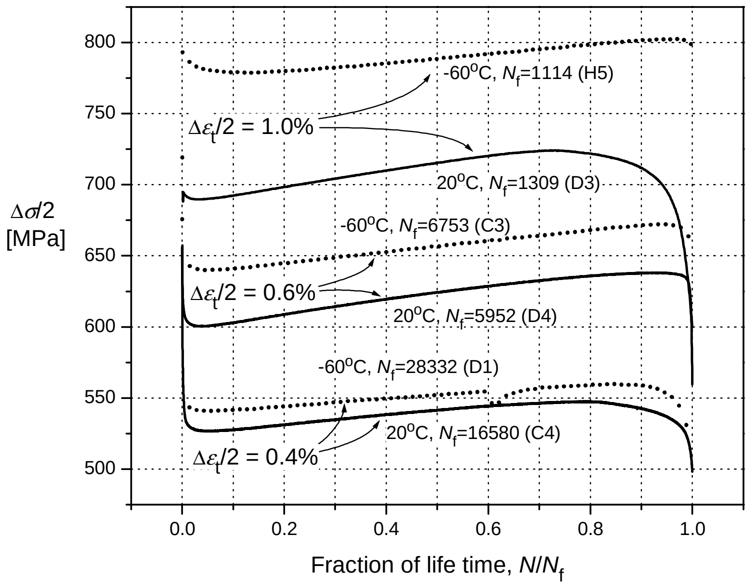

Figure 3: Stress amplitude development for tests run at both +20°C (black lines) and –60°C (dotted lines). The cycle number has been normalised to the total number of cycles to failure for each test. The kink in the sample D1 curve is caused by a temporary increase of extensometer temperature.

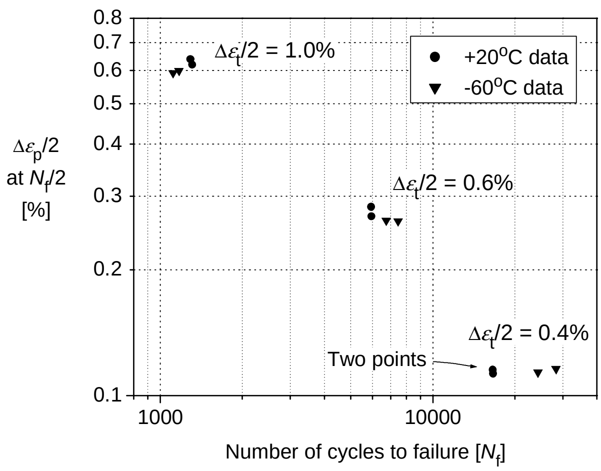

Figure 4: Fatigue life versus plastic strain amplitude

In Figure 4 the plastic strain amplitude (taken at half the number of cycles to failure) versus the total number of cycles to failure is plotted for each sample. It is evident that for low strain amplitudes, a larger number of cycles to failure results from testing at a low temperature, while for higher strain amplitudes the tests performed at room temperature exhibit longer lives.

5 CONCLUSIONS

Fatigue tests at constant total strain amplitudes ($\Delta\varepsilon_t/2$) 0.4%, 0.6% and 1.0% were performed on UIC R8T material. The testing temperatures used were +20°C and at –60°C. The most important results are as follows:

1. The stress amplitude levels at –60°C as compared to those at 20°C are ca 5% higher at the lowest strain amplitude level, about 10% higher at $\Delta\varepsilon_t/2$=0.6%, and ca 15% higher at $\Delta\varepsilon_t/2$=1.0%. The scatter in stress amplitude levels between parallel tests is small and can be justified by similar deviations in hardness.
2. All samples exhibit initial softening during approximately the first 10% of the total life and thereafter change to a state of slow continuous hardening that proceeds until ca 90% of the life has been expended. After this stage, a dominant crack forms and grows with increasing speed which significantly decreases the load bearing area. The degree of initial softening is much greater for samples run at lower strain amplitudes. Samples run at the highest strain amplitude show stronger hardening than those run at lower strain amplitudes.
3. The observed scatter in number of cycles to failure (N_f) is small between identical tests, which is a testament of the even quality of the material tested, and the careful sample preparation and test control. Deviations are less than 1.5% for all strain levels at 20°C and less than 5–15% for tests run at –60°C. Increased defect sensitivity is most likely the main cause for increased scatter at –60°C.
4. It is evident that at high strain amplitudes, the fatigue properties can be worse at lower temperature. As crack initiation at defects can occur also after single overloads, fatigue testings on prestrained samples would be very interesting.

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