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Chapter 33
Influence of Heat Treatment Temperature on Fatigue Toughness in Medium-Carbon High-Strength Steels

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Abstract Current research has demonstrated that the tempering temperature affects the martensitic transformation of medium-carbon high-strength steels. This temperature plays an important role in the final microstructure, percentage ratios of martensite to ferrite phases and, consequently, in the mechanical properties and the fatigue response. So far, the relationship between the martensitic tempering temperature and the cyclic deformation properties is not clearly understood. Moreover, the effect of the martensitic tempering temperature on fatigue toughness has not been studied yet. Therefore, this paper aims to study, in a systematic manner, the fatigue toughness of medium-carbon high-strength steels heat treated at different temperatures under fully reversed strain-controlled conditions.

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33.1 Introduction

Modern railway industry, driven by economic and environmental factors, faces an urgent need to improve efficiency, safety, and reliability. In particular, higher train speeds and heavier traffic loads lead to larger wheel/rail contact forces, which can result in rolling contact fatigue failure. In order to avoid this major concern, new generations of rail materials are being developed, aiming at enhancing the mechanical properties, prolong service life, and reduced cost. Despite the development of new materials, medium-carbon high-strength steels remain outstanding materials in this challenging scenario, mainly due to their superior features, namely the strength-to-weight ratio, toughness, ductility, among others. The development of new materials for applications subjected to cyclic loading requires not only the deep understanding of mechanical behaviour but also reliable fatigue design approaches. Despite the long debate over the last decades on the identification of a universal fatigue damage parameter, no consensus has been found. In general, fatigue models are expressed in terms of stress-based, strain-based, or energy-based relationships [1]. Energy-based relationships are quite versatile and have been successfully applied, either for uniaxial or for multiaxial loading [2–4].

Although not new in the literature, the concept of cumulative strain energy density has been less studied, and its capabilities and limitations are not completely clear, particularly when we are dealing with new engineering materials, such as the new medium-carbon high-strength steels, which can be produced for different heat treatment temperature programmes. In the literature, a power relationship between the cumulative strain energy density and the number of cycles to failure is reported in the low-cycle fatigue regime, either at room temperature or at elevated temperature, for different materials, such as ferritic steels, structural steels, rail steels, austenitic stainless steels, high-strength steels, and bainitic steels, among others. As recently demonstrated in the paper by Martins et al. [5], this well-defined relationship opens the possibility to develop new energy-based approaches to estimate the fatigue lifetime.

This paper aims at studying the effect of tempering temperature on cumulative strain energy density, also known as fatigue toughness, for medium-carbon high-strength steels. At a first stage, we perform a series of low-cycle fatigue tests, under strain-controlled conditions, for different strain amplitudes and heat treatment temperatures. After that, the fatigue toughness for each condition is computed using the stress–strain response collected in the experiments. Finally, the values determined for each tested condition are compared.

Table 33.1 Nominal chemical composition (wt%) of the tested steel

C	Mn	Si	Cr	Mo	Fe
0.18	2.9	1.7	0.8	0.26	Rem.

33.2 Experimental Procedure

In this research, a medium-carbon high-strength steel subjected is studied in the low-cycle fatigue regime for different strain amplitudes and heat treatment temperatures. The nominal chemical composition, in weight percentage, of the tested steel, the 18Mn3Si2CrMo steel, is summarised in Table 33.1. The steel was austenitised at 900 °C, then tempered for 1 h for four different temperatures (i.e. 190 °C, 230 °C, 275 °C, and 315 °C), and finally cooled, in air, to room temperature.

Specimens were machined in accordance with the ASTM E606 standard with a 10 mm long and a 5 mm diameter gauge section. Gauge sections were polished to a scratch-free condition using carbide papers and diamond-based paste. Low-cycle fatigue tests were performed in a conventional servo-hydraulic machine, at strain control mode, under fully reversed conditions, using sinusoidal waves and a constant strain rate, i.e. $d\varepsilon/dt = 6 \times 10^{-3}$. The studied strain amplitudes (ε_a) were 0.50%, 0.65%, 0.80%, and 1.00%. Tests started in compression and stopped when the specimens separated into two parts.

33.3 Results and Discussion

33.3.1 Low-Cycle Fatigue Tests

Examples of the typical stress–strain response observed for different heat treatment temperatures for the same strain amplitude ($\varepsilon_a = 1.0\%$) are presented in Fig. 33.1. As can be seen in the figure, the cyclic plastic response affected the heat treatment temperature from the first cycle to the second cycle, and then showed a strain-softening behaviour until the total failure. We can clearly see that after the mid-life cycle, this strain-softening behaviour is more and more evident, leading to distorted hysteresis loops with a very limited portion of the linear elastic tensile part. This means that the strain energy density changes considerably during the tests.

The effect of the heat treatment temperature on cyclic plastic behaviour can be better analysed via the analysis of stress amplitude during the tests. Figure 33.2 plots the stress amplitude against the number of cycles for four different strain amplitudes (1.0%, 0.80%, 0.65%, and 0.5%) and two different heat treatment temperatures (190 and 315 °C). It is clear from the figure that the material does not exhibit a fully saturated state for all the plotted cases. In several situations, particularly at higher strain amplitudes, the stress amplitude changes continuously with the number of

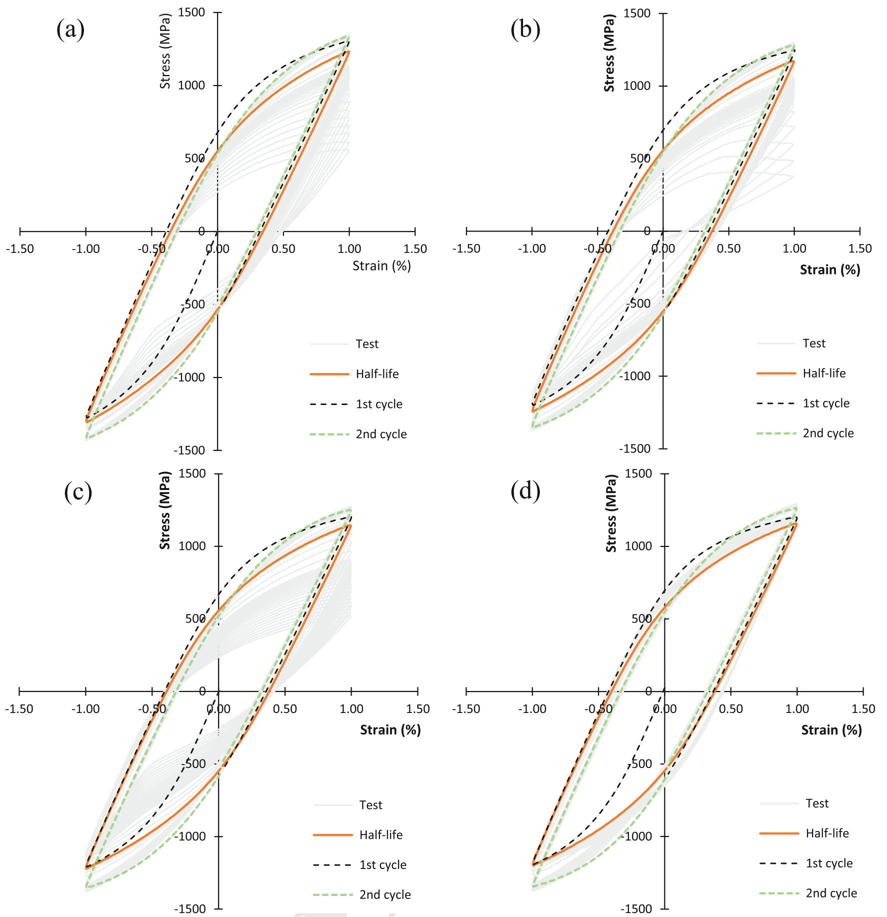

Fig. 33.1 Cyclic stress–strain response of the tested material for a strain amplitude of 1.0% and a heat treatment temperature of: **a** 190 °C, **b** 230 °C, **c** 235 °C, and **d** 315 °C

cycles, without reaching a stable value; in other cases, although the stable value is reached, it occurs in a relatively short period of the test. On the contrary, at lower strain amplitudes, the stabilised response is clearer, and the stress amplitude tends to be constant for a long period of the test. A close look at the figure also shows that the effect of heat treatment process is more pronounced at lower quench temperatures.

The relationship between the plastic strain energy density (ΔW_P) at the mid-life cycle and the number of cycles to failure for the different heat treatment temperatures is exhibited in Fig. 33.3. In this study, the plastic strain energy density, i.e. the area of the hysteresis stress–strain loop was computed numerically using about 200 data points collected in the tests for each cycle. As can be seen, the fitted curves do not follow a unique curve, which suggests that ΔW_P is affected by the heat treatment temperature. Regarding the total strain energy density, defined here as the sum of

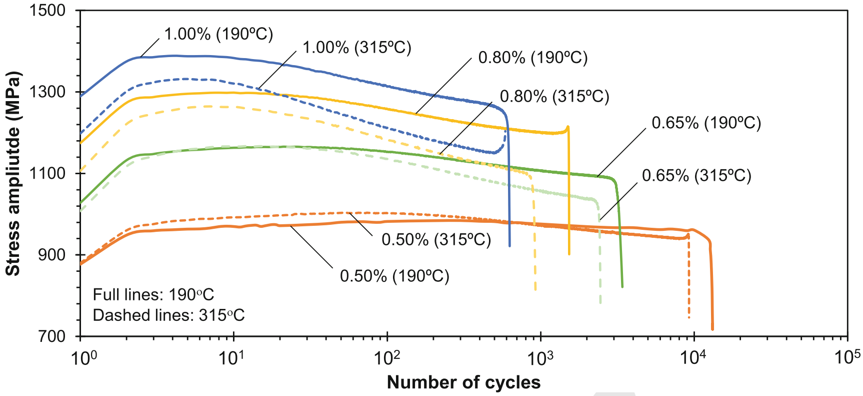

Fig. 33.2 Stress amplitude versus number of cycles for different strain amplitudes (0.50%, 0.65%, 0.80%, and 1.00%) and two different heat treatment temperatures (190 and 315 °C)

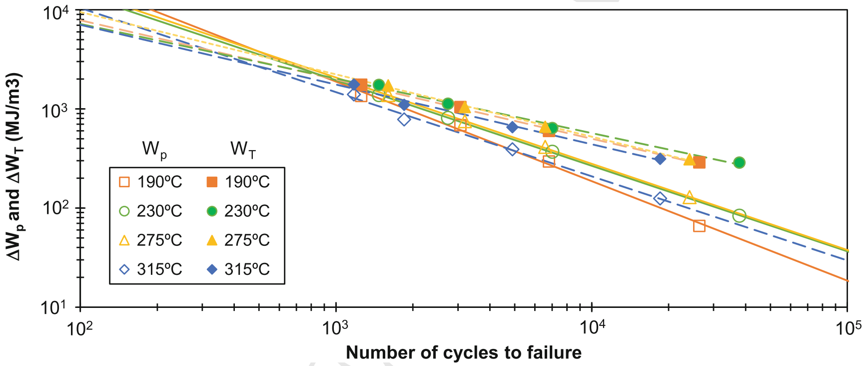

Fig. 33.3 Total strain energy density (ΔW_T) versus number of cycles to failure and plastic strain energy density (ΔW_P) versus number of cycles to failure for different heat treatment temperatures

both the plastic and the tensile positive components, the conclusions are similar. Figure 33.3 plots the total strain energy density (ΔW_T) at the mid-life cycle against the number of cycles to failure for the different heat treatment temperatures. In a similar manner to the plastic strain energy density, the fitted functions are also affected by the heat treatment temperature, leading to different energy-life responses, which are not an attractive solution in terms of fatigue design, since it requires an individual experimental programme for each temperature, in order to define the material fatigue properties.

If we analyse the energy response in terms of cumulated values, i.e. cumulated plastic strain energy density (W_P) and cumulated total strain energy density (W_T), the conclusions are different. Here, the cumulated values were computed numerically, using a cycle-by-cycle integration basis. The typical trends found in this study are exhibited in Fig. 33.4. As can be seen in the figure, unlike the previous case, the

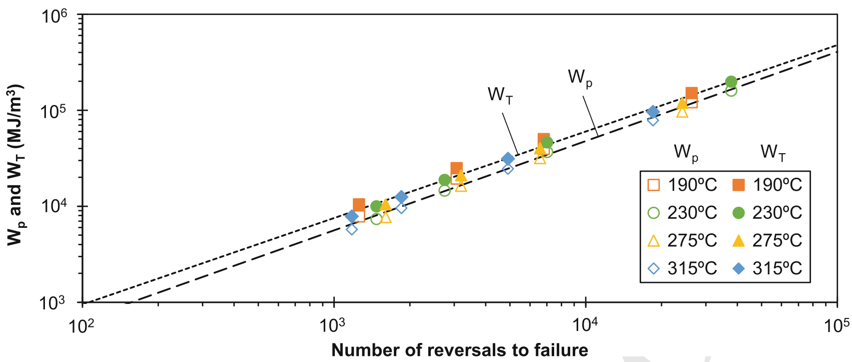

Fig. 33.4 Cumulated strain energy density versus number of cycles to failure for different strain amplitudes and heat treatment a temperatures. W_T represents the cumulated total strain energy density, and W_P represents the cumulated plastic strain energy density

relationships between the cumulated plastic strain energy and fatigue life, and the cumulated total strain energy density and the fatigue life, can be defined using single functions (see dashed lines). In fact, the data points are collapsed in the same trends, irrespective of the heat treatment temperature. This approach deeply simplifies the design approach, since a single function can be used, which reduces costs and time associated with the characterisation of material fatigue properties.

33.4 Conclusions

This study aimed at analysing the effect of heat treatment temperature on cumulated strain energy density, also known as fatigue toughness, in medium-carbon high-strength steels tested in the low-cycle fatigue regime. The experimental programme comprised four different tempering temperatures (190 °C, 230 °C, 275 °C, and 315 °C) and four strain amplitudes (0.50%, 0.65%, 0.80%, and 1.0%). The following conclusions can be drawn:

- the tested steel, irrespective of the tempering temperature, exhibited an initial strain-hardening behaviour, in the first two cycles, and then showed a strain-softening behaviour until the total failure;
- the cyclic stress–strain response was clearly affected by the heat treatment temperature. In most cases, a fully saturated stage was not achieved, leading to significant changes in the hysteresis loop shapes throughout the entire test;
- the energy-life relationships, defined in terms plastic or total components using the mid-life cycle, were strongly affected by the heat treatment temperature. Individual energy-life functions were required to fit the data;

- the energy-life relationships (plastic and total components), defined in terms of cumulated values, were not affected by the heat treatment temperature. A single function could fit the results, which is an interesting outcome.

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