

Chapter 33

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



G. Wheatley, R. Branco, J. A. F. O. Correia, R. F. Martins, W. Macek, Z. Marciniak, and M. Szala

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.

G. Wheatley

College of Science and Engineering, James Cook University, Bebegu Yumba Campus Building 15-124, Townsville, QLD 4811, Australia

R. Branco (✉)

Department of Mechanical Engineering, CEMMPRE, University of Coimbra, Coimbra, Portugal
e-mail: ricardo.branco@dem.uc.pt

J. A. F. O. Correia

Faculty of Engineering, INEGI and CONSTRUCT, University of Porto, Porto, Portugal

R. F. Martins

Department of Mechanical and Industrial Engineering, Nova School of Science and Technology, UNIDEMI, Campus de Caparica, 2829-516 Caparica, Portugal

W. Macek

Faculty of Mechanical and Ocean Engineering, Gdańsk University of Technology, 11/12 Gabriela Narutowicza, 80-233 Gdańsk, Poland

Z. Marciniak

Faculty of Mechanical Engineering, Opole University of Technology, Mikolajczyka 5, 45-271 Opole, Poland

M. Szala

Department of Materials Engineering, Faculty of Mechanical Engineering, Lublin University of Technology, 36D Nadbystrzycka Street, 20-618 Lublin, Poland

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2022

G. Lesiuk et al. (eds.), *Fatigue and Fracture of Materials and Structures*, Structural Integrity 24, https://doi.org/10.1007/978-3-030-97822-8_33

1



11 **Keywords** High-strength steels · Cyclic plastic behaviour · Heat treatments ·
12 Tempering · Fatigue toughness

13 33.1 Introduction

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

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

41 This paper aims at studying the effect of tempering temperature on cumulative
42 strain energy density, also known as fatigue toughness, for medium-carbon high-
43 strength steels. At a first stage, we perform a series of low-cycle fatigue tests,
44 under strain-controlled conditions, for different strain amplitudes and heat treatment
45 temperatures. After that, the fatigue toughness for each condition is computed using
46 the stress–strain response collected in the experiments. Finally, the values determined
47 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

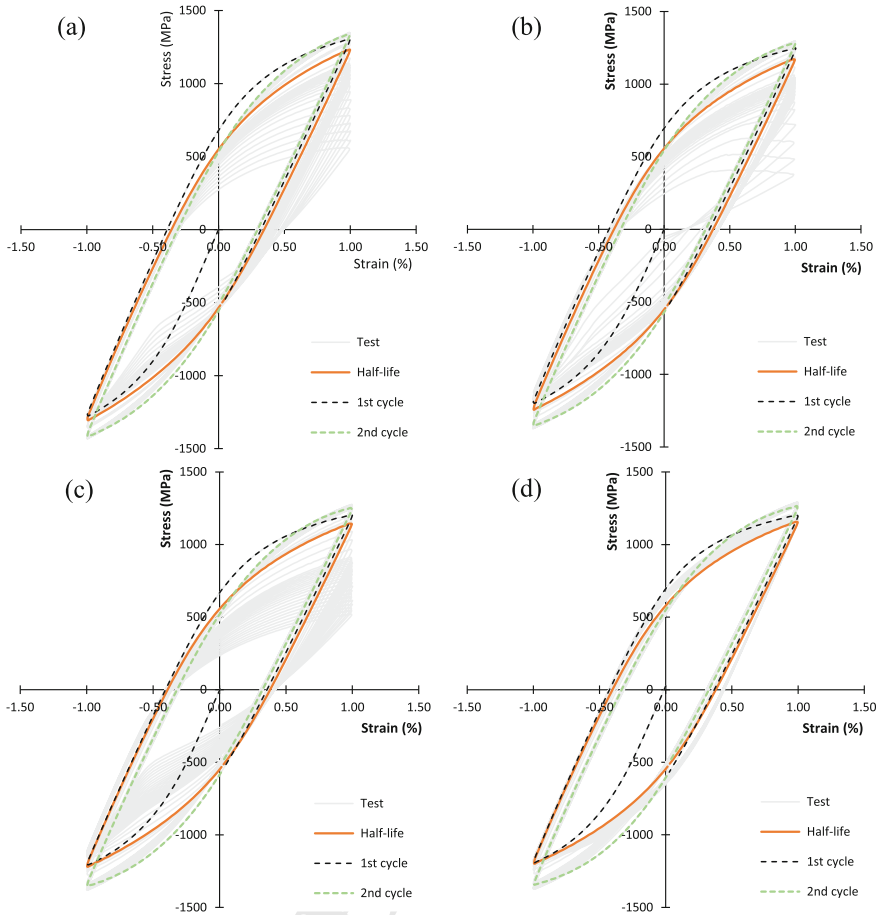


Fig. 33.1 Cyclic stress–strain response of the tested material for a strain amplitude of 1.0% and a heat treatment temperature of: **a** 190 °C, **b** 230 °C, **c** 235 °C, and **d** 315 °C

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

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

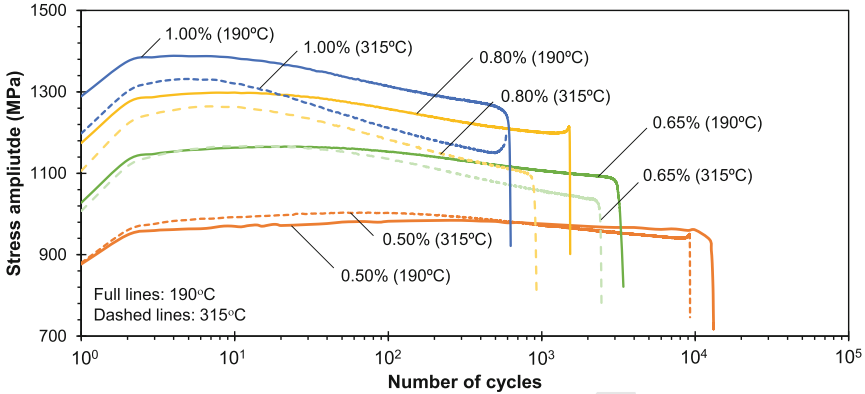


Fig. 33.2 Stress amplitude versus number of cycles for different strain amplitudes (0.50%, 0.65%, 0.80%, and 1.00%) and two different heat treatment temperatures (190 and 315 °C)

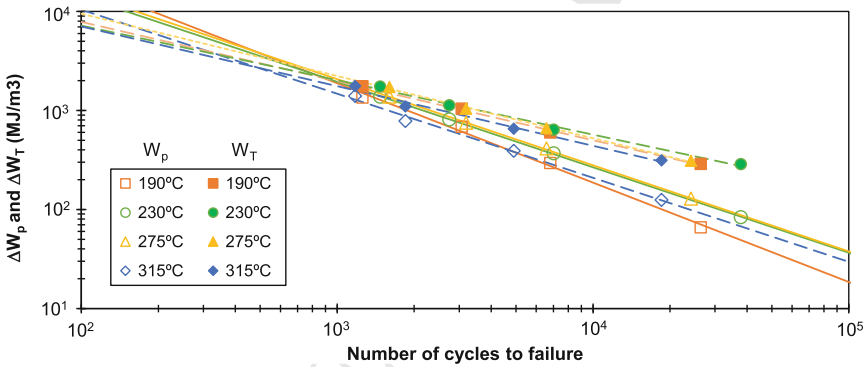


Fig. 33.3 Total strain energy density (ΔW_T) versus number of cycles to failure and plastic strain energy density (ΔW_P) versus number of cycles to failure for different heat treatment temperatures

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

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

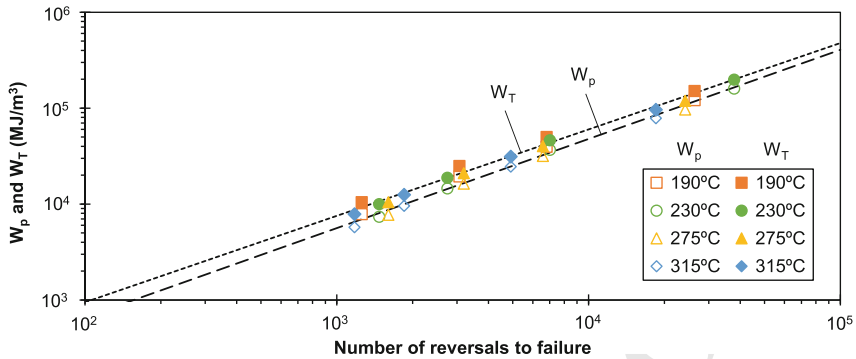


Fig. 33.4 Cumulated strain energy density versus number of cycles to failure for different strain amplitudes and heat treatment at temperatures. W_T represents the cumulated total strain energy density, and W_P represents the cumulated plastic strain energy density

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;

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

130 **Acknowledgements** This research is sponsored by FEDER funds through the programme
131 COMPETE—Programa Operacional Factores de Competitividade—and by national funds through
132 FCT—Fundação para a Ciência e a Tecnologia—under Project UIDB/00285/2020.

133 References

- 134 1. Branco R, Costa JD, Borrego LP, Berto F, Razavi S, Macek W (2021) Comparison of
135 different one-parameter damage laws and local stress-strain approaches in multiaxial fatigue
136 life assessment of notched components. *Int J Fatigue* 151:106405
137 2. Liao D, Zhu SP (2019) Energy field intensity approach for notch fatigue analysis. *Int J Fatigue*
138 127:190–202
139 3. Lesiuk G, Szata M, Rozumek D, Marciniak Z, Correia JAFO, Jesus AMP (2018) Energy response
140 of S355 and 41Cr4 steel during fatigue crack growth process. *J Strain Anal Eng Des* 53:663–675
141 4. Nejad R, Berto F (2021) Fatigue fracture and fatigue life assessment of railway wheel using
142 non-linear model for fatigue crack growth. *Int J Fatigue* 153:106516
143 5. Martins RF, Branco R, Long XL (2020) Fatigue life assessment in bainitic steels based on the
144 cumulative strain energy density. *Appl Sci* 10:7774