Low cycle fatigue analysis of ferrite-martensite dual-phase steel using advanced cyclic plasticity models

V Singh1,5, S K Basantia1,3, A Bhattacharya3,4, D Das3 and N Khutia1

1Department of Aerospace Engineering and Applied Mechanics, IIEST Shibpur, India
2Department of Mechanical Engineering, KIIT, Bhubaneswar, India
3Department of Metallurgy and Materials Engineering, IIEST Shibpur, India
4Presently at Dept. of Metallurgical and Materials Engineering, IIT Kharagpur, India

Abstract. A computational model has been developed to predict the low cycle fatigue (LCF) characteristics of ferrite-martensite dual phase (DP) steel. LCF results of DP steel performed at strain amplitudes varying from 0.3% to 1.5% show initial cyclic hardening followed by cyclic softening behavior. Finite element simulation employing Chaboche model fails to capture the initial cyclic hardening behavior specifically at lower strain amplitudes. To predict the observed cyclic hardening and softening characteristics of DP steel with a progressive number of cycles, Ohno-Wang cyclic plasticity model has been modified by altering the yield function, which is formulated by incorporating a memory stress function. All the material parameters have been calibrated considering hysteresis loop of the first cycle of LCF result of ±1.5% uniaxial strain. The developed material model has been integrated with ABAQUS 6.14 finite element package to perform the LCF simulation. A comparison between simulation and experimental results for all strain amplitudes reveals that the proposed model has the better capability to predict the overall LCF characteristics of DP steel.

1. Introduction

In the recent years, ferrite-martensite dual-phase (DP) steel is increasingly used in automotive and many other applications due to its excellent combination of mechanical properties. DP steel is a low carbon, low-alloy steel that exhibits high strength and good formability as well as continuous yielding with high initial work hardening rate (Ghassemi-Armaki H. et al., 2014). Evaluation of fatigue behavior of DP steel is essential since automobile components are subjected to fluctuating loading during service. Analysis of cyclic plastic deformation behavior plays a vital role to understand the fatigue and failure mechanism.

In past few decades, various constitutive models have been developed to simulate the cyclic plastic deformation of materials. Paul et al. (2011) have examined the different cyclic plastic characteristics like Bauschinger effect, cyclic hardening/softening, strain range effect, loading history memory, ratcheting, mean stress dependent hardening, mean stress relaxation and non-proportional hardening of SA333 C-Mn steel and 304 LN stainless steel. Haupt and Kamlah (1995) have modelled cyclic hardening, cyclic softening, cyclic mean stress relaxation, and additional non-proportional cyclic hardening by introducing hardening function for back stress and yield stress. Ohno (1982) has introduced the concept of a non-hardening region in the plastic strain space, assuming that the materials do not exhibit isotropic hardening when plastic strain changes inside the region under cycling loading. Ohno and Kachi (1986) have proposed a cyclic plasticity model for non-linear hardening material that describes the cyclic hardening phenomenon as well as the transient elasto-plastic behavior. Ohno and Wang (1993, 1994) have introduced the kinematic hardening rule which simulate ratcheting accurately.

In the present study, an effort has been made to investigate the cyclic plastic deformation characteristics of ferrite-martensite DP steel. Finite element analyses using Chaboche and modified
Ohno-Wang have been performed to investigate the applicability of these models to predict the cyclic plastic behavior of DP steel.

2. Material and Methods

A low-carbon low-alloy steel (see table 1) was subjected to intercritical annealing (725 °C, 1 h) treatment followed by water quenching to develop ferrite-martensite DP structure. Microstructure characterization of heat treated steel was carried out following standard metallographic techniques and specimens were etched using 2% nital solution. Optical micrograph in figure 1 reveals the uniform distribution of martensite (black) phase in the ferritic (white) matrix confirming the development of ferrite-martensite DP steel. Heat treated round bars were machined to produce cylindrical tensile (6.5 mm diameter and 25 mm gauge length) and LCF (6.5 mm diameter and 15 mm gauge length) specimens as per ASTM E8-00 and ASTM E606-12, respectively. The machined specimens were mechanically polished up to 1 µm diamond to achieve mirror finish surface.

| Element | Wt.% |
|---------|------|
| C       | 0.21 |
| Mn      | 1.30 |
| Si      | 0.25 |
| S       | 0.007|
| P       | 0.011|
| Ni      | 0.22 |
| Cr      | 0.20 |
| Mo      | 0.14 |
| V       | 0.004|
| Cu      | 0.12 |
| Fe      | Balance |

Tensile tests were performed using Instron 8801 machine at a nominal strain rate of 1x10⁻³ s⁻¹. Strain controlled symmetric tension-compression tests were performed using Instron-8862 model, a close-loop electromechanical actuator controlled machine. Tests were performed at constant strain range of 1x10⁻³ s⁻¹ using a triangular waveform at four different strain amplitudes of 0.3%, 0.5%, 1.0% and 1.5% until failure. An extensometer of gauge length 12.5 mm was mounted on the test specimen to control the strain. Instron LCF software was used to record the LCF test results.

3. Finite Element Analysis

Finite element simulation of LCF characteristics was performed by using ABAQUS-6.14 commercial software considering eight noded reduced integration axisymmetric element (CAX8R). The modified Ohno-Wang model has been incorporated in the finite element code and ABAQUS through user-defined programming subroutine (UMAT).

3.1. Cyclic plasticity model

3.1.1. Chaboche model

This model is based on the work of Lemaitre and Chaboche (1990). The incremental back stress based on the kinematic hardening model can be expressed as:

\[
d\sigma_i^{(t)} = C_i^{(t)} \varepsilon_i^{(t)} \left[ \frac{1}{\sigma_0} \left( \sigma - a_i \right) - \gamma_i^{(t)} \right] d\varepsilon_i^{(t)} + \frac{1}{C_i^{(t)}} \dot{a}_i^{(t)}
\]  

(1)

Yield surface expression can be written as:

\[
\sigma^0 = \sigma_0 + Q \left[ 1 - e^{-\frac{\gamma^2}{2\theta^2}} \right]
\]

(2)
where, $\sigma_0$ is the size of yield surface at zero plastic strain, $Q_a$ and $b$ are the calibrated material parameters. Different material parameters required for Chaboche model were determined using the experimental stress-strain data of initial cycle of 1.5% strain amplitude. The calibrated material parameters are summarized in Table 2.

3.1.2. Proposed model (Ohno-Wang model with proposed formulation of yield)

Ohno and Wang (1993) have proposed the concept of critical state of dynamic recovery on each back stress component based on plastic strain increment. This rule is composed of $M$ number of back stress components in the kinematic hardening rules, which is described as:

$$d\sigma = \sum_{i=1}^{M} d\sigma^i$$

(3)

$$r^{i} = \frac{c^{i}}{\gamma^{i}}$$

(4)

$$d\sigma^i = \frac{2}{3}c^{i} \langle d\varepsilon^p \rangle - \gamma^{i} \left[ \frac{d\varepsilon^p}{f(a^{i})} \right] \left( f(a^{i}) \right)^{m^i}$$

(5)

where, $f(a^{i})=\left[ \frac{3}{2} a^{i} : a^{i} \right]$ and $c^{i}, \gamma^{i}$ ($i=1,2,3,...,M$) are material constants. $d\sigma^i$ is increment of back stress components.

Hysteresis loops of first few cycles of investigated DP steel reveal that the tensile peak increases but the compressive peak reduces from 1$^{st}$ to 8$^{th}$ cycles (figure 2). This phenomenon is commonly referred to as isotropic hardening of the material. It has been further noticed from the experimental results that the magnitude of isotropic hardening or softening is dependent on the applied strain amplitude. In the present study, a model is proposed to precisely simulate the observed LCF behavior in ferrite-martensite DP steel; this model is henceforth referred to as DP-LCF. For this purpose, a memory stress parameter has been introduced in the proposed model. Khutia et al. (2014) have earlier described the concept of memory stress surface. The memory stress surface expands outward when the magnitude of total back stress $\frac{2}{3}|a|$ is more than the memory stress, $s$; however, it contracts when the back stress is less than the memory stress. The increment of memory stress, $d\sigma$, is governed by the expression:

$$d\sigma = \frac{dp}{p_0} \left( \frac{2}{3} |a| - s \right) \text{ and } s(0) = 0$$

(6)

where, $dp$ is the rate of accumulated plastic strain, $s$ is the memory stress and $p_0$ is a positive material constant which determines the range of plastic strain memory. The magnitude of stabilized memory stress in equation (6) is equal to the maximum radius of locus of $a$, i.e., $\frac{2}{3} |a|$.

In the present formulation, a variation of yield stress has been incorporated in the Ohno-Wang kinematic hardening model to capture the combined cyclic hardening and softening characteristics of DP steel. A plot between stress amplitude versus accumulated plastic strain has been derived from the
experimental data. The best fitted curve (coefficient of determination: R = 0.99) has been established with the help of an exponential function, expressed as:

\[ \sigma_a = \sigma_{ao} + A_1 \exp \left( \frac{dp}{t_1} \right) + A_2 \exp \left( \frac{dp}{t_2} \right) \]  

(7)

where, \( \sigma_a \) is stress amplitude, \( \sigma_{ao} \) is the initial cycle stress amplitude, \( dp \) is accumulated plastic strain, \( A_1, A_2, t_1, \) and \( t_2 \) are material parameters which influence the hardening and softening behavior. The above-mentioned formulation is used as a variation of yield with accumulated plastic strain by modifying the initial yield i.e., \( \sigma_{ao} \) as expressed:

\[ \sigma_y = \sigma_{yo} + A_1 \exp \left( \frac{dp}{t_1} \right) + A_2 \exp \left( \frac{dp}{t_2} \right) \]  

(8)

In equation (8), the first exponential function takes care of the softening behavior, whereas the second exponential function controls the hardening effect. \( \sigma_{yo} \) is the initial yield stress.

Incorporating equation (8) in the proposed constitutive model with Ohno Wang kinematic hardening rule, simulations have been performed for all strain ranges varying from \( \pm 0.3\% \) to \( \pm 1.5\% \). It was observed that the stress amplitude versus no of cycle obtained from simulation over predict the experiment test data in all cases except for 1.5% strain amplitude. In order to minimize the deviation, a graph between memory stress and \( \sigma_{yo} \) is plotted and the curve fitting has been done. The equation of \( \sigma_{yo} \) obtained from the curve fitting is expressed as a function of memory stress, \( s \), which is given by:

\[ \sigma_{yo} = \psi_1 + \psi_2 \exp(s/t_s) \]  

(9)

where, \( s \) is memory stress. Again, \( A_2 \) is calibrated and expressed as a function of initial yield i.e., \( \sigma_{yo} \), which is given by:

\[ A_2 = -\sigma_{yo} + \delta \]  

(10)

All material parameters calibrated for proposed DP-LCF model has been listed in table 2.

| Table 2: Material parameters for Chaboche and proposed DP-LCF models. |
|--------------------------|--------------------------|
| Elastic parameters: \( E = 200 \) GPa, \( \mu = 0.33 \) |
| Chaboche model parameters( for \( i = 1 \rightarrow 3 \)) obtained from initial cycle hysteresis loop |
| \( c^l \) = 70000, 2600, 10784 |
| \( \rho^l \) = 5002009 |
| Hardening parameters: \( Q_a = -28.33 \) and \( b = 1.5 \) |
| DP-LCF model parameters( for \( i = 1 \rightarrow 12 \)) obtained from initial cycle hysteresis loop |
| \( c^l \) = 153609.83, 23634.7964075.5664533.4145292.53 |
| 39923.9925412.9421022.43, 3682.239176.918281.31, 10334.65 |
| \( \rho^l \) = 1018.5312941718.522296.244329.1833343.3159, 448580 |
| \( m^l \) to \( m^{l^2} = 1.2 \) |
| \( A_1 = 28.95, t_1 = -0.5, t_2 = -0.02, t_3 = 22.88 \) |
| \( \psi_1 = 16670, \psi_2 = 0.06021, \delta = 5 \) |

4. Simulation Results and Discussion

The proposed DP-LCF model has been developed by analysing the variation of cyclic hardening and softening at various strain amplitudes with progressive cycles. Finite element simulation has been performed using Chaboche (Lemaître and Chaboche, 1990) and the proposed DP-LCF models. Comparison of stress amplitude with number of cycles between the simulation and the experiment for \( \pm 1.5\%, \pm 1\%, \pm 0.5\% \) and \( \pm 0.3\% \) strain ranges have been presented in figure 3. Experimental stress amplitude versus number of cycle data shows a combined cyclic hardening and softening effect. The amount of initial hardening is higher at higher strain ranges and the hardening effect is significantly
less at lower strain ranges. In contrary, the numbers of hardening cycles are less at higher strain ranges and the number of hardening cycle increases as the strain amplitude decreases. These characteristics are better correlated with the proposed DP-LCF model than the Chaboche model (figure 3) simulation results. DP-LCF model is able to predict peak hardening characteristics of the material with a progressive number of cycles. Figure 3 shows, the simulation results obtained by Chaboche model could not be able to capture the combined hardening and softening behavior of DP steel. At ±1.5% strain range Chaboche model under predict the experimental data but for ±0.3% strain range, it shows a better prediction with experiment. At intermediate strain ranges i.e., ±1.0% and ±0.5%, Chaboche model over predict the experiment results.

![Comparison of amplitude vs. number of cycles between simulation and experiment for DP steel at strain amplitude of (a) 1.5%, (b) 1.0%, (c) 0.5% and (d) 0.3%](image)

A comparison of hysteresis loops for 1st cycle, peak amplitude cycle and 200th cycle between simulation (using Chaboche and DP-LCF models) and the experiment are shown in figure 4. It shows that the hysteresis loop generated from DP-LCF model has well predicted the experimental results at ±0.5% strain range but both the results deviate from the experiment at for higher strain range (e.g., ±1.5% strain amplitude).

**Conclusions**

In the present study, LCF behavior of ferrite-martensite dual phase (DP) steel is investigated at room temperature. A new model DP-LCF has been proposed by modifying isotropic hardening formulation of the Ohno-Wang kinematic hardening rule. The simulation results with the developed model are validated with the experimental data. Based on the finite element analysis and experimental observations, the following conclusions have been drawn:

- Ohno-Wang model with the proposed isotropic hardening model (DP-LCF) shows a better correlation with the experimental behavior of DP steel under LCF.
- Mixed behavior of strain range dependent initial hardening and subsequent softening of the material is due to the change in the isotropic hardening characteristics of the material.
exponential yield function is suggested in the proposed model which enables to simulate the material characteristics accurately under cyclic strain controlled loading.

➢ In the constitutive modeling, the yield stress is formulated as a function of memory stress which efficiently demonstrates the effect of strain amplitudes on the response of the material as observed in the experiment.

![Figure 4](image)

**Figure 4.** Comparison of hysteresis loops between experiment and simulation for 1.5% strain amplitude (a) cycle-1, (b) cycle-2, (c) cycle-200, and for 0.5% strain amplitude (d) cycle-1, (e) cycle-8 and (f) cycle-200.

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