Damage mechanics analysis of a weld steel microstructure using testing and macro and micro level simulations

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Abstract

The goal is to study the damage of structural steel weld HAZ zone at the weld toe. The macroscopically active and residual stresses are applied to a microscopic FEM model containing the microstructural elements of several grains and phases and the outer surface topography. Also damage FEM mechanics are used. The progress of damage is observed by simulations. The plastic deformation progress to damage was also studied with analytical continuum models of two phases. The model of Mileiko proved satisfactory. These methods can be used in designing welds optimally.

1 Introduction

The first goal is to study and develop damage analysis methods in micro and macro level simulations. The second goal is to apply these to a HAZ zone at weld toe of a structural steel. The third goal is to develop methodology for designing metallurgically optimal microstructures. The yield stress, plastic flow and damage of multiphase structures have been studied at micro and macro levels using various methods. Among these are continuum mechanical theories which do not predict inherently the effect of absolute dimensions.
The theory of Mileiko [1] is based on plastic instability approach to fiber and matrix type composites. The theory of Tomota and Kuroki [2] is based on effect of internal stresses of ellipsoidal inclusions which both may work harden. Dislocation mechanics approach can be used. Karlsson and Linden [3,4] have considered ferrite-pearlite structures and have described the flow stress of the matrix in terms of geometrically necessary dislocations. This approach has also been used by Fischmeister & al. [5]. Nonlinear finite element modelling has been used by [3,4,5], Sundström [6] and Jinoch & al. [7]. The applicability of the theories of [1] and [2] have been studied critically by Bhadeshia and Edmonds [8] and Davies [9]. Now an application of Mileiko’s theory is presented and also nonlinear MARC FEM [10] modelling as by Martikka [11]. The statistics of crack nucleation in a deformed microstructure is considered by Goto & al. [12].

2 Methods and experimental work

The following methods are used. One is to use flow and work hardening continuum models for predicting the composite failure using component nonlinear models. The second method is to use nonlinear MARC FEM [10] to calculate residual stresses with a 3D model and a 2D model to study the critical zone. The principles are shown in Fig. 1.

![Schematics illustrating the principles of the methods used.](image)

- a) The 3D FEM model
- b) Location of the 2D model
- c) The 2D model is one quarter of the whole model showing a surface crack and a slip line extending from it.
- d) Tensile test definitions.
3 Results

3.1 Results of using flow and work hardening theories

3.1.1 Background of the theory of Mileiko

The theory of Mileiko [1] is based on plastic instability approach to fibre/matrix type composites. It has been shown [8,9] that this theory can predict satisfactorily changes in tensile strength and ductility of dual phase steels as a function of the martensite percentage even though the martensite is not in fibrous form. Necessary assumptions for a satisfactory validity of Mileiko’s theory are:

a. the stress state is not inhomogeneous [8]
b. the power law strength models can be fitted satisfactorily well

The material model for two phases is described in Fig.2.

![Figure 2: The interconnection of the nominal stress-true strain test curves and the conventional rule of mixtures. A linear and a nonlinear model for the composite strength $\sigma_c$ are shown.](image)

Mileiko’s [1] theory applies when both fibres and matrix show appreciable ductility. The ultimate tensile strength of a homogeneous ductile material is determined by the condition of plastic instability. The nominal stress $\sigma = Q/S_0$ reaches a maximum value when a rod reaches an unstable state, that is necking begins under constant volume $V$. Now $Q$ is load force and $S_0$ is initial value of the cross sectional area $S$. If the stress-strain curve is expressed in true stress $s$, true strain $\varepsilon$, coordinates
The true stress \( s \) and the nominal stress \( \sigma \) are approximated by a power law function

\[
s = K \epsilon^n, \quad s_f = K_f \epsilon^{n_f}, \quad s_m = K_m \epsilon^{n_m}, \quad \sigma = se^{-\epsilon} = K \epsilon^n e^{-\epsilon}
\]  

(2)

where \( K \) and \( n \) are constants. Assuming incompressibility of the volume \( V = V_o \), the load is maximum at instability

\[
Q = \sigma S_0 = sS = \sigma \epsilon^\epsilon S_0 = K \epsilon^n e^{-\epsilon} S_0
\]

\[
\frac{dQ}{d\epsilon} = 0 \rightarrow \frac{d}{d\epsilon} \left( \epsilon^n e^{-\epsilon} \right) = ne^{n-1} e^{-\epsilon} - \epsilon^n e^{-\epsilon} = 0 \rightarrow n = \epsilon
\]  

(3)

Whence the nominal stress at instability is

\[
\sigma_u = Kn^n e^{-n} = s_u e^{-n} \quad K = \sigma_u n^{-n} e^n \rightarrow
\]

\[
\sigma = K \epsilon^n e^{-\epsilon} = \sigma_u n^{-n} \epsilon^n e^{-\epsilon} = \sigma_u \left( \frac{\epsilon}{n} \right)^n e^{n-\epsilon}
\]  

(4)

In the metal composite there are two phases \( f \) and \( m \). The rule of mixture gives for the total composite

\[
\sigma_c(\epsilon) = \sigma_f(\epsilon)V_f + \sigma_m(\epsilon)V_m, \quad \sigma_f(\epsilon) = K_f \epsilon^{n_f} e^{-\epsilon} =
\]

\[
= \sigma_{fu} \left( \frac{\epsilon}{n_f} \right)^{n_f} e^{n_f-\epsilon}, \quad \sigma_m(\epsilon) = K_m \epsilon^{n_m} e^{-\epsilon} = \sigma_{mu} \left( \frac{\epsilon}{n_m} \right)^{n_m} e^{n_m-\epsilon}
\]  

(5)

\[
\sigma_c(\epsilon) = \sigma_f(\epsilon)V_f + \sigma_m(\epsilon)V_m = \left[ V_f K_f \epsilon^{n_f} + V_m K_m \epsilon^{n_m} \right] e^{-\epsilon}
\]

\[
= V_f K_f F(\epsilon) + V_m K_m M(\epsilon)
\]  

(6)

The instability of the composite is achieved when the necking starts with the condition (7)

\[
\frac{d\sigma_c(\epsilon)}{d\epsilon} = \sigma_{f,\epsilon}(\epsilon)V_f + \sigma_{m,\epsilon}(\epsilon) = V_f K_f F_{,\epsilon}(\epsilon) + V_m K_m M_{,\epsilon}(\epsilon) = 0
\]
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This is linear on volume fraction \( V_f \) and it may be solved as

\[
V_f = \frac{1}{1 + \beta \frac{\varepsilon_c - \varepsilon_m}{\varepsilon_f - \varepsilon_c} \varepsilon_m - \varepsilon_f}
\]

\[
\beta = \frac{\sigma_{mu} \varepsilon_f \varepsilon_f}{\sigma_{fu} \varepsilon_m \varepsilon_m \exp \varepsilon_f}
\]

The tensile strength of the composite as the nominal stress is

\[
\sigma_c = \sigma_m V_m L_m + \sigma_f V_f L_f \quad V_m = 1 - V_f
\]

\[
L_m = \left( \frac{\varepsilon_c}{\varepsilon_m} \right)^{\varepsilon_m} \exp(\varepsilon_m - \varepsilon_c) \quad L_f = \left( \frac{\varepsilon_c}{\varepsilon_f} \right)^{\varepsilon_f} \exp(\varepsilon_f - \varepsilon_c)
\]

3.1.2 Application of the theory to a steel

These models are applied to analyse tensile test results of a steel of type Fe 37B SFS 200 with composition (in wt%) 0.13 C, 0.20 Si, 0.51 Mn, 0.017 P, 0.028 S, 0.15 Cr, 0.19 Ni (11). This steel is not well applicable by the Mileiko’s theory since it has a pronounced discontinuous yielding range. Secondly ferrite pearlite structures pearlite may have a smaller effect on the yield strength than predicted by the normal rule of mixtures. The tensile tests are analysed in the following detail steps.

1. First the 0.2 % yield strength is obtained as

\[
R_{p0.2} = \frac{F_p}{S_0} = 28000 \text{N/129 mm}^2 = 217 \text{N/mm}^2.
\]

2. The nominal tensile strength is necking force divided by the initial area

\[
R_m = \frac{F_m}{S_0} = 46200 \text{N/129mm}^2 = 358 \text{mm}^2
\]

3. The constancy of volume initially and at necking strain gives

\[
V_0 = V_g \quad S_0 L_0 = S_g L_g \rightarrow S_g = 129 \text{mm}^2/50.8 \text{mm}/63.3 \text{mm}=104 \text{ mm}^2
\]

4. The true tensile strength at necking point \( g \) is

\[
R_{mt} = \frac{F_m}{S_g} = 46200 \text{N/104 mm}^2 = 444 \text{ MPa}
\]

5. The extensions are

\[
\varepsilon_g = \ln(1 + A_g) = 0.244
\]

Now the parameters of the simple power law are determined as

\[
n = \frac{\ln(R_{mt} / R_p)}{\ln(\varepsilon_g / \varepsilon_p)} = 0.1526 \quad K = \frac{R_{mt}}{\varepsilon_p^n} = 560 \text{MPa}
\]
Matrix For ferrite matrix the following values are assumed:

$R_{pm} = 200$, $\varepsilon_{pm} = 0.002$, at UTS $R_{mtm} = 430$ MPa the necking strain is $\varepsilon_{gm} = 0.22$. Then $n_m$ and $K_m$ are calculated as

$$n_m = \frac{\ln(R_{mtm}/R_{pm})}{\ln(\varepsilon_{gm}/\varepsilon_p)} = 0.163 \quad , \quad K_m = \frac{R_{mtm}}{\varepsilon_{gm}^n} = 550\text{MPa}$$

The model gives for the yield and UTS of the matrix

$$\sigma_{mp}(\varepsilon_p) = K_m \varepsilon_p^n m e^{-\varepsilon_p} = 212 \quad , \quad \sigma_{mu}(n_m) = K_m n_m^n m e^{-n_m} = 350$$

Pearlite For the pearlite the following values are assumed:

$R_{pf} = 460$, $\varepsilon_{pf} = 0.002$, at UTS $R_{mrf} = 550$ MPa the necking strain is $\varepsilon_{gf} = 0.18$. Then $n_f$ and $K_f$ are calculated

$$n_f = \frac{\ln(R_{mrf}/R_{pf})}{\ln(\varepsilon_{gf}/\varepsilon_p)} = 0.04 \quad , \quad K_f = \frac{R_{mrf}}{\varepsilon_{gf}^n} = 589\text{MPa}$$

Experimental data for the composite true stress -true strain can be fitted also with two models

$$s = R_p + K\varepsilon^n = 217 + 316\varepsilon^{0.218}$$

$$s = R_p + H(\varepsilon - \varepsilon_p) = 217 + 1050(\varepsilon - 0.002) \quad \text{(10)}$$

The straight line slope is $H = (444 - 217)/(0.218 - 0.002) = 1050$
The simulated models based on Mileiko’s theory

Linear models of true stress–true strain are used in FEM models. The work hardening rates and the models for the matrix (m) and phase (p) and the composite (c) are

\[ H_m = 1111 = (423 - 200)(.202 - .002) = 1111 \]
\[ H_n = 463 = (553 - 460)/(.202 - .002) \]
\[ H_p = 941 = (423 - 233) \]

\[ s_m = R_{pm} + H_{mt}(\varepsilon - \varepsilon_{pm}) = 200 + 1111 \cdot (\varepsilon - .002) \]
\[ s_f = R_{pf} + H_{ft}(\varepsilon - \varepsilon_{pf}) = 460 + 463 \cdot (\varepsilon - .002) \]  (11)
\[ s_c = R_{pc} + H_{ct}(\varepsilon - \varepsilon_{pc}) = 233 + 941 \cdot (\varepsilon - .002) \]

The curves calculated with these models fit reasonably well with the nonlinear curves in Fig. 3.

3.2 Results with FEM simulations

Models are shown in Fig. 1. FEM was used to calculate residual weld stresses by 3D FEM and microstructural damage with 2D FEM models.

3.2.1 Residual weld stresses by three dimensional FEM model

Macroscopic residual weld stresses are obtained by weld cooling simulations, Fig. 4. At the HAZ of the weld toe the weld residual stresses are applied to a microscopic FEM model containing the microstructural elements on a mesoscopic level of several grains and phases and the outer surface topography, Fig. 5.

Figure 4: FEM simulation of a 3D model of the weld structure. a) The deformed form due to residual weld stresses and b) the distribution of residual stresses acting in surface tangent direction after welding shown along a line from the weld.
3.2.2 Results with the two dimensional FEM models

The principle of the 2D models is shown in Fig.1 and results in Fig.5.

Figure 5: Results of MARC FEM simulations with notch N, and no notch. Darkening gray indicates increasing intensity. a) FEM model for microstructure, N b) Mises stress distribution, no N, max 763MPa, c) tensile stress curves up to strain 0.0415 along tensile stress directions, top curves along mid plate, lower curve along top surface, d) optical micrograph with 0.011 mm grain size, e) damage as void volume fractions up to 0.11, with N and f) equivalent plastic strain up to 0.2 with N.
When the stress is increased from $0.73 R_p$ to $0.93 R_p$ the parameters change. For defects: $m_D = 4.5 \rightarrow 8.1$, $n_D = (6.2 \rightarrow 0.5) \times 10^4$, $p = 0.24 \rightarrow 0.09$. For slip lines: $m_s = 7.2 \rightarrow 10.7$, $n_s = (7.3 \rightarrow 0.6) \times 10^4$, $q = 0.76 \rightarrow 0.91$.

\[ F(N) = pF_D(N) + qF_S(N), \quad p + q = 1 \]

\[ F_D(N) = 1 - \exp\left(-\left(\frac{N}{n_D}\right)^{m_D}\right) \]
\[ F_S(N) = 1 - \exp\left(-\left(\frac{N}{n_s}\right)^{m_s}\right) \]  \hspace{1cm} (14)

These models indicate that at high stresses the slip bands are dominant locations for the microcrack initiation life in line with FEM simulations.

### 4 Discussion

The results show that damage is largest close to the maxima of equivalent plastic strain concentrations. This is in line with experimental observations that at high stresses fatigue cracks preferably nucleate at slip bands. These methods can be used in designing metallurgically optimal fatigue resistant and weldable microstructures for machine constructions.

### References


