Monotonic and Cyclic Stress-Strain Behaviour of a High Strength Steel

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Abstract
The monotonic and cyclic stress-strain response of a C-Mn steel in two different microstructural conditions, banded ferrite-pearlite and ferrite-bainite, has been investigated. A general conclusion has been drawn about cyclic response of the material. Hardening behaviour above the yield point is analysed by using a model for linear and parabolic hardening.

Riassunto
È stata studiata la risposta deformazione-sollecitazione monotonica e ciclica di un acciaio al C e Mn in due diverse condizioni di microstruttura. Si è tratta una conclusione generale sulla risposta ciclica del materiale. Il comportamento di incrudimento sopra il limite elastico è stato analizzato usando un modello per l'incrudimento lineare e parabolico.

Introduction

Fatigue is recognised as a failure mechanism arising from cyclic loading. Crack initiation and propagation both involve the concept of cyclic accumulated damage. The detail of damage structure can be related to the material's cyclic stress strain response. The processes of crack initiation and growth are controlled by the material properties which will themselves be modified by the effects of cyclic stress-strain loading. Monotonic stress strain relationship controls simple deformation, ultimately fracture, while the cyclic relationship controls the finite life fatigue process. Bauschinger discovered that steel could show both cyclic strain hardening and softening and that the Wohlers fatigue limit represents a kind of cyclic yield point.

Apart from cyclic softening or hardening, a semi-log plot is adequate to differentiate the three regimes, elastic, elastic-plastic and plastic, which are due to differences in deformation behaviour that occur as the strain amplitude varies [1, 2]. Elastic-plastic regime is related to the formation and development of persistent slip bands and are known to be the sites of crack initiation and early crack propagation [3]. In elastic regime, plastic deformation and some strain accumulation occurs but no persistent slip bands are formed at strain amplitude below the yield point. This strain amplitude and its associated threshold stress have been related to the fatigue limit of the material [4, 5]. Cyclic stress-strain response is the term given to describe the relationships between the flow stress and the cyclic strain. It is useful for understanding the fatigue process and for design consideration against fatigue.

The work presented in this paper will study the stress-strain behavior of the C-Mn steel under two different microstructural conditions. The analysis will be carried out using the model for linear and parabolic hardening.

Material and experimental detail

The material used in this investigation contains weight % of 0.12C, 1.38 Mn and 0.26 Si and is used where a good combination of toughness and weldability is required. Tests were performed on material suitably prepared to simulate two different microstructures, a normalized banded ferrite-pearlite and ferrite-bainite. The ferrite-bainite microstructure was obtained by heat treatment; namely austenitizing at 1150°C, cooling down in the furnace to 800°C and then oil quenching.

The monotonic tests were performed on standard tensile specimens. The multistep uniaxial cyclic tests were carried out on hour-glass shape specimens. The method used to calculate shear stress and shear strain in hour-glass specimen is presented elsewhere [6].

Results and discussion

Stress-strain behaviour

The ratio of the cyclic yield stress to monotonic yield stress is 0.63 for banded ferrite-pearlite microstructure and 0.64 for heat treated material. Figs. 1 and 2 shows a comparison of monotonic and cyclic stress-strain behaviour of both microstructures, which indicate a cyclic softening as the cyclic curves are below the monotonic curves. Such behaviour was expected because the material is classified as high strength material [7]. For an initially high strength material, the dislocation density is high and cycling causes a re-arrangement of the dislocations into a new configuration that offers less resistance to deformation and therefore the material shows cyclic softening. When the material is soft, the dislocation density is initially low, but due to cyclic deformation, the dislocation density increases rapidly which induces a significant hardening [8].

Irrespective of whether the material cyclically hardens or softens, cycling at stresses well above the yield point, hardening always takes place. In general the hardening is due to the resistance offered to dislocations movement. All theories of work hardening depend on this assumption and the basic idea of hardening, that some dislocations becomes anchored within the crystal and act as a source of internal stress which opposes the motion of other dislocations. The degree and type of hardening depends on the density and distributions of locked dislocations but is, either of a parabolic or linear type.

Parabolic hardening

Parabolic hardening is always associated with dislocations arranging themselves into low energy configurations, such as cell boundaries and therefore the main resistance to dislocation motion is from short-range intersects. Assuming that the cell form square net works of size d_c, Rios [9], proposed that the number of dislocations in d_c^2 is $2d_c/\varkappa$ and the dislocation density p is;

$$\varrho = \frac{2d_c/\varkappa}{d^2_c} = \frac{2}{\varkappa \cdot d_c} \tag{1}$$

$\varkappa$ represents the dislocation separation in the cell walls. The stress required to push a dislocation through the wall is;

$$\tau \simeq \frac{G \cdot b \cdot \pi \cdot d_c}{4} \tag{2}$$

where G is the shear modulus and b is the Burger vector. Dislocations are assumed to pile-up against the cell boundaries and therefore, the stress ahead of the pile-up (= $n\tau$), during plastic flow, should equal the strength of the wall, given by equation (2), i.e,

$$n\tau = \frac{G \cdot b \cdot \pi \cdot d_c}{4} \tag{3}$$

where n is the number of dislocations and is defined as;

$$n = \frac{\tau = d_c}{G \cdot b}$$

then equation (3) becomes;

$$\tau = \frac{1}{2} \cdot G \cdot b \cdot \varrho^{0.5} \tag{4}$$

The displacement per unit length of dislocation is $b \cdot d_c/4$ and therefore the total shear strain (γ) is defined as;

$$\gamma = \varrho \cdot b \cdot \frac{d_c}{4}$$

$$\varrho = \frac{4 \cdot \gamma}{b \cdot d_c} \tag{5}$$

In terms of shear stress and shear strain equation (4) with equation (5) becomes;

$$\tau = G \cdot \left(\frac{b}{d_c} \cdot \gamma\right)^{0.5} \tag{6}$$

The hardening in this case is proportional to the square root of the shear strain.

Linear hardening

Under cyclic loading it is difficult to specify the mode of hardening. Due to cyclic stress dislocations may approach towards one another and eventually will lock and then take no further part in the deformation process. But the other sources will remain active and their dislocations will continue to create point defects, vacancies and interstitials [10]. The dislocations generated at the sources in each cycle move along the slip planes until they are stopped at the grain boundaries and pile-up. The back stress generated by these dislocation groups produces the hardening. For deformation to proceed the flow stress required to move dislocations along the slip band under cyclic loading, should equal the back stress and is defined as [9];

$$\tau_{cy} = \frac{\varphi \cdot n' \cdot G \cdot b}{\pi \cdot l} \tag{7}$$

where φ is the relief factor affecting the pile-ups, n' number of dislocations in the pile-up and l represents the spacing between slip bands.

Considering that each dislocation loop expands to the diameter of the grain "d" with n' dislocations in each slip band is $n'4d$. The dislocation density p is defined as;

$$\varrho = \frac{n' \cdot 4d}{d^2 l} \tag{8}$$

from equation (7) and (8);

$$\tau_{cy} = \varphi \cdot G \cdot b \cdot \varrho \cdot \frac{d}{4\pi} \tag{9}$$

which shows that hardening depends on the length of the slip band, which is approximately equal to the grain diameter "d" and on the dislocation density which also depends on grain size.

By the combination of equations (5) and (9), taking $d_c = d$;

$$\tau_{cy} = \varphi \cdot \frac{G}{\pi} \cdot \gamma \tag{10}$$

which represents a linear relationship between back stress across a grain and the shear strain.

It is clear from Figs. 1 and 2 that the monotonic stress-strain curve is parabolic beyond the yield point while the cyclic stress-strain curve represents almost a linear relationship between shear stress and shear strain.

To verify the hardening behaviour under steady and cyclic loading, the theoretical flow stress was calculated using equations (6) and (10), for both microstructures and is shown in Figs. 3 and 4 along with experimental data corresponding to the plastic region of the stress-strain curve which shows good agreement with the theoretical curves. Fig. 3, which represents results from the monotonic tests, shows some deviation of experimental points from the theoretical curves. It is probably due to the annihilation of dislocations which reduces the actual dislocation density to values below those predicted by eq. (5).

Conclusions

The material under both microstructural conditions shows cyclic softening behaviour.

Hardening well above the yield point follows a parabolic and a linear relationship between flow stress and shear strain in monotonic and cyclic loading, respectively, in both microstructures.

Acknowledgements

The authors are thankful to, Government of Pakistan for a research scholarship for K. Hussain and Alcan International for SIRIUS assistant directorship of research for E.R. de Los Rios. Thanks are due to A. Navarro, University of Seville (Spain) for useful discussion.

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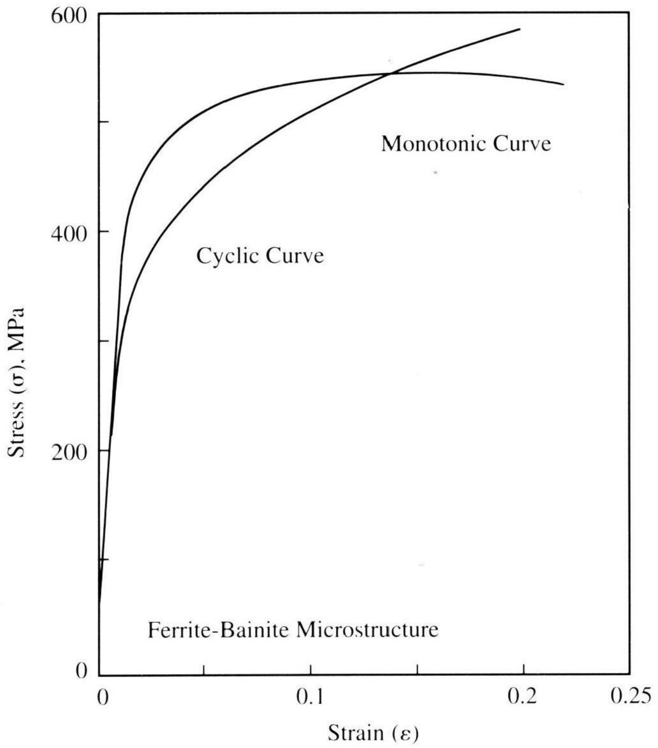

Fig. 1:
Monotonic and cyclic stress strain curves.

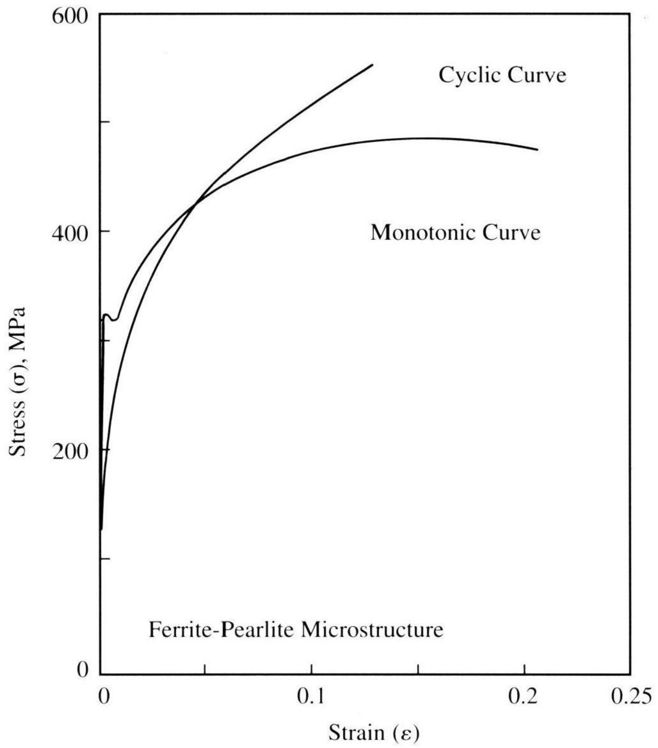

Fig. 2:
Monotonic and cyclic stress strain curves.

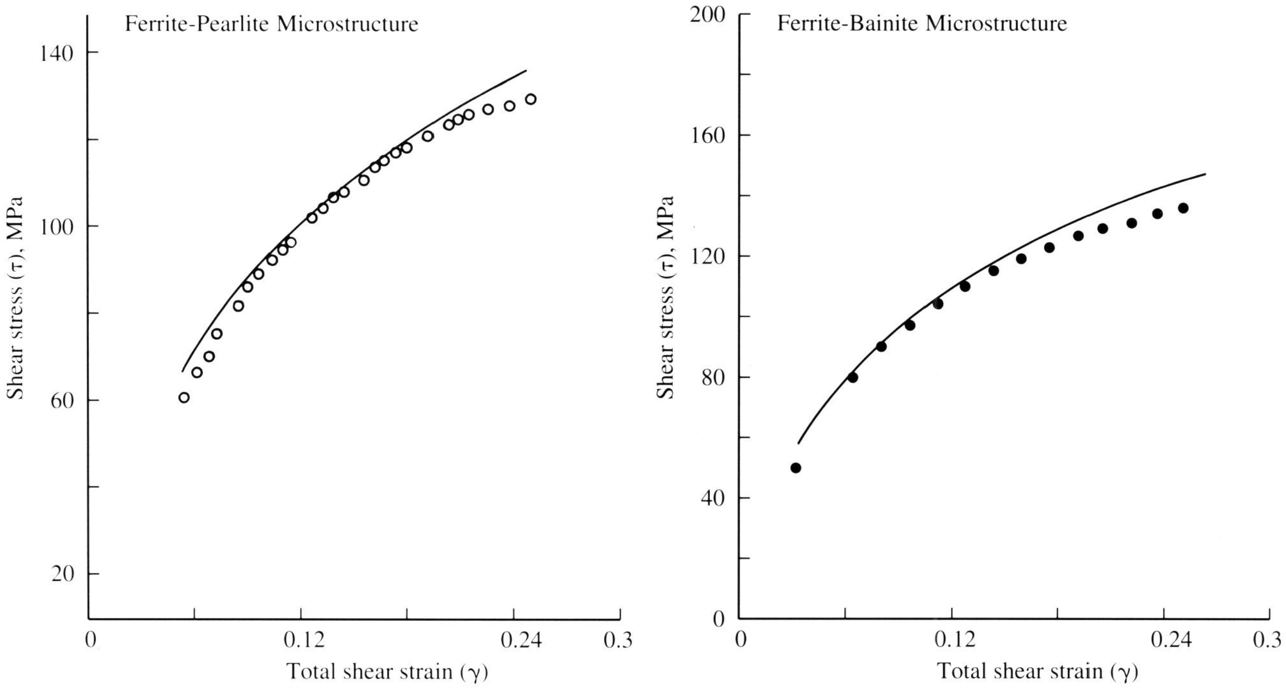

Fig. 3:
Strain hardening under monotonic loading. Curves represent theoretical predictions.

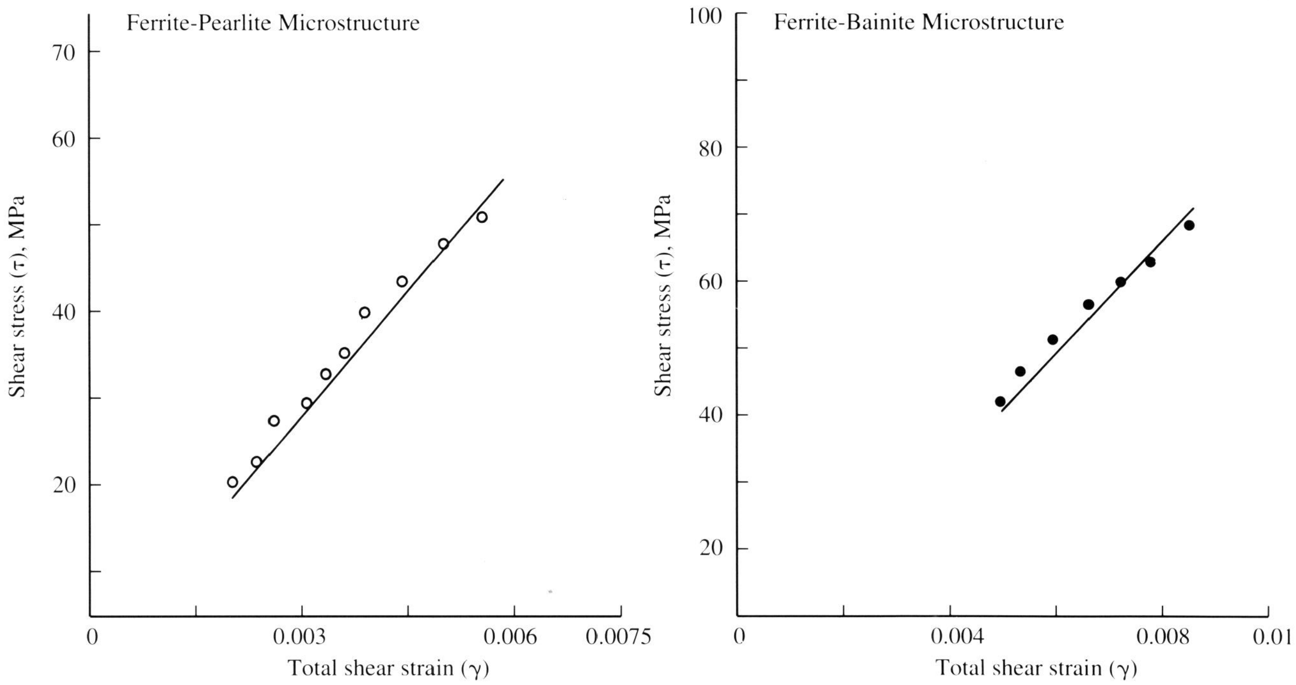

Fig. 4:
Strain hardening under cyclic loading. Curves represent theoretical predictions.