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THE INFLUENCE OF CHEMICAL COMPOSITION ON THE CYCLIC BEHAVIOUR OF FERRITE-PEARLITE STEELS

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1. INTRODUCTION

The relationships between chemical composition, microstructure and tensile properties of pearlitic steels have been studied extensively in recent years, [1, 2, 3]. The most common approach has been to evaluate various strengthening mechanisms in these steels and to represent the findings in the form of regression equations. Similar techniques have been employed by Grozier and Bucher [4] and Nishioka and Nishikawa [5] to study the effects of composition and microstructure on the fatigue limit of steels.

In recent years the importance of cyclic stress-strain relationships in fatigue studies has been emphasized. Tomkins [6] has suggested that stress or strain life fatigue curves can be predicted from the parameters of a cyclic stress-strain curve. Morrow [7], using an alternative approach, has demonstrated that the slopes and intercepts of the two components of a total strain-life curve can be determined from the monotonic fracture stress and ductility and the cyclic strain hardening exponent (n'). Experimental evidence, which is available to support both theories [8, 9] clearly demonstrates the importance of cyclic properties in fatigue. In addition to the importance of cyclic stress-strain relationships in the more fundamental studies of fatigue there is a rapidly increasing demand for such information in the solution of practical fatigue problems by computer based analysis [10, 11].

The present work was undertaken to study the effects of chemical composition and microstructure on cyclic stress-strain data of a range of ferrite-pearlite steels. The steels considered formed a wide range of plain carbon steels from which many components used on British Railways are manufactured. The implications of the results on the fatigue behaviour of these steels is also considered.

2. EXPERIMENTAL PROCEDURE

The work programme was based on a factorially designed experiment in which the elements Carbon, Silicon and Manganese were each fixed at three equally separated levels. Two heat treatment variables were also included so that variations in microstructure for each steel composition could be introduced. Monotonic and cyclic stress-strain curves were obtained for conditions representing one third of the complete factorial design.

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The steels tested were all produced using a vacuum melting process in order to minimize the non-metallic inclusion level. The compositions of the steels are listed in Table 1.

All the tests were carried out using smooth, axial 5 mm diameter specimens with a parallel gauge length of 7 mm. Two different types of tests were performed in a servo-hydraulic testing machine:

(a) Monotonic tension tests at a strain rate of approximately 0.005/sec. The stress-strain data was calculated from the measured engineering stress-strain relationships. The true fracture stress was corrected to allow for the presence of triaxiality due to necking [12].

(b) Incremental step tests to establish the cyclic stress-strain curves.

3. RESULTS

The mechanical properties of interest were equated with the volume fraction and properties of the individual constituents in the microstructure. In the analysis of results the following model was selected:

$$Ps = f\alpha \cdot P\alpha + fc \cdot Pc$$

where Ps = a property of the steel, Pα and Pc = the individual properties of the ferrite and carbide phases respectively and fα and fc are the volume fractions of ferrite and carbide respectively.

$$fc = K_1 \ (\%\ \text{Carbon})$$

$$f\alpha = (1 - fc)$$

$$P\alpha = K_2 + K_3 \ (\%\ S_1) + K_4 \ (\%\ \text{Mn}) + K_5 \ (\bar{\lambda}^{-1/2}).$$

This is an extension of the Hall-Petch relationship [13, 14] in which $\bar{\lambda}$ = mean ferrite path. ($\bar{\lambda} = f\alpha \cdot d + (1 - f\alpha)(S^0 - fc)$ where S^0 = interlamellar spacing, pearlite, and d = average grain diameter.

$$Pc = \text{Constant } K_6$$

K_1 to K_6 are constants.

Combining:

$$P_s = \left\{K_1 (\%\ C)\right\} \left\{K_2 + K_3 \ (\%\ S_i) + K_4 \ (\%\ \text{Mn})\right\} + K_5 \ (\bar{\lambda}^{-1/2}) + K_6 (K_1 \ (\%\ C)) \ .$$

Simplifying:

$$P_s = C + C_1 \ (\%\ S_i) + C_2 \ (\%\ \text{Mn}) + C_3 \ (\%\ C) + C_4 \ (\bar{\lambda}^{-1/2}) \ ,$$

where C to C_4 are constants.

In the majority of steels tested the structure was fully pearlite and $\bar{\lambda}^{-1/2}$ was virtually a constant. Therefore, if this term is incorporated into the overall equation constant, only the compositional variables appear in the regression equations. Using this approach, the following equations were produced.

3.1 Monotonic σ-ε Results

$$\sigma_y = 110 + 303 \ (\%\ C) + 73 \ (\%\ Si) + 66 \ (\%\ Mn) \qquad \text{MPa}$$

$$\sigma_f = 480 + 567 \ (\%\ C) + 139 \ (\%\ Si) + 165 \ (\%\ Mn) \qquad \text{MPa}$$

$$\varepsilon_f = 1.18 - 1.02 \ (\%\ C)$$

where

σ_y = yield stress,

σ_f = fracture stress, and

ε_f = fracture ductility.

3.2 Cyclic σ-ε Results

$$\sigma_y' = 115 + 49 \ (\%\ C) + 57 \ (\%\ Si) + 27.6 \ (\%\ Mn) \qquad \text{MPa}$$

$$n' = 0.149 + 0.151 \ (\%\ C) - 0.037 \ (\%\ Si)$$

$$K' = 423 + 1\ 870 \ (\%\ C) \qquad \text{MPa}$$

where

σ_y' = cyclic yield stress,

n' = cyclic strain hardening exponent, and

K' = cyclic strength coefficient.

In general the individual deviations from the mean lines, as expressed above, are within a reasonable level, as shown in Figure 1.

4. DISCUSSION

The results illustrate a number of interesting compositional features and their influence on fatigue properties.

4.1 Yield Strengths σ_y and σ_y'

The effect of increasing C, Si and Mn was to increase both the monotonic and cyclic yield strength. Under cyclic conditions all elements (particularly carbon) had a much reduced effect on yield stress than under monotonic conditions, with the effect that the cyclic yield stress was always lower than the monotonic yield stress. This indicates that cyclic softening will occur in all the steels examined at strain levels just beyond that corresponding to the cyclic yield stress.

σ_y' is often considered to be the fatigue limit of a material. In this respect it can be seen that Silicon has a greater effect on the fatigue limit than carbon.

4.2 Cyclic Strain Hardening Exponent n'

The cyclic strain hardening exponents were measured up to a total strain of 0.015. In this region, which is particularly relevant to fatigue studies, an excellent linear relationship existed between log stress amplitude and log plastic strain. It can be seen from the equation that increases in carbon content had the effect of increasing n' whereas increases in silicon had the opposite effect. Manganese variations did not significantly affect the values of n'. These results are shown graphically in Figure 2.

The equations for the monotonic fracture stress and fracture strain are as expected. Increasing all three elements has the effect of increasing σ_f and only carbon content affects the fracture strain.

Using the Morrow equation [7] for predicting total strain-life curves, i.e.,

$$\varepsilon_t = \varepsilon_f' \; (2Nf)^c + \frac{\sigma_f'}{E} \; (2Nf)^b \; ,$$

and the notation of Feltner and Beardmore [15], the overall effects of compositional variations on fatigue life can be assessed, e.g.,

In the low cycle region:

As Carbon ↑ , n' ↑ , ε_f' ↓ , c becomes less negative, the overall effect is very small.

As Silicon ↑ , n' ↓ , ε_f' is unchanged, c becomes more negative, the overall effect is detrimental.

As Manganese ↑ , n', ε_f' and c are unchanged, the overall effect is zero.

In the high cycle region:

As Carbon ↑ , n' ↑ , σ_f' ↑ , b becomes more negative, the overall effect is beneficial.

As Silicon ↑ , n' ↓ , σ_f' ↑ , b becomes less negative, the overall effect is beneficial.

As Manganese ↑ , n' and b are unchanged, σ_f' ↑ , the overall effect is slightly beneficial.

5. CONCLUSIONS

1) All the steels examined cyclically soften at strain levels just beyond the cyclic yield stress.

2) Increasing carbon content has the effect of increasing the cyclic strain hardening exponent whereas Silicon has the opposite effect.

3) Increases in all elements caused an increase in the fatigue limit of the steels. The relative order of effectiveness was Silicon, Carbon and Manganese.

4) In the low cycle region of a strain-life curve, a beneficial effect can only be achieved by reducing Carbon, Silicon or Manganese.

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Table 1 Material Compositions

CAST NUMBER	C	Si	Mn	S	P	Cu	O_2	N	Su	Al
10	0.30	0.30	0.54	0.013	0.004	0.04	0.0005	0.001	0.005	0.005
31	0.32	0.28	1.01	0.012	0.006	0.05	0.0013	0.002	0.014	"
34	0.32	0.27	1.44	0.010	0.005	0.06	0.0011	0.001	0.005	"
28	0.30	1.20	0.54	0.011	0.003	0.05	0.0005	0.001	0.005	"
37	0.34	1.09	1.03	0.012	0.006	0.04	0.0018	0.002	0.010	"
43	0.32	1.10	1.60	0.013	0.006	0.05	0.0017	0.002	0.006	"
07	0.29	2.04	0.54	0.013	0.004	0.05	0.0010	0.001	0.005	"
48	0.32	1.83	1.02	0.011	0.003	0.01	0.0028	0.002	0.010	0.03
72	0.32	1.91	1.51	0.011	0.004	"	0.0010	0.002	"	"
41	0.50	0.33	0.56	0.012	0.004	0.03	0.0005	0.001	0.006	0.005
32	0.51	0.28	0.99	0.011	0.007	0.07	0.0009	0.001	1.010	"
35	0.52	0.29	1.50	0.011	0.006	0.04	0.0005	0.002	0.006	"
42	0.51	1.11	0.57	0.012	0.004	0.05	0.0013	0.001	0.005	"
38	0.51	1.13	1.08	0.011	0.007	0.06	0.008	"	0.007	"
45	0.51	1.09	1.51	0.013	0.006	0.07	0.0011	"	0.007	"
70	0.50	1.84	0.52	0.013	0.003	0.01	0.0035	0.002	0.01	0.03
71	0.52	1.90	1.01	0.011	0.003	"	0.0018	"	"	0.02
73	0.49	1.80	1.46	0.011	0.004	"	0.0005	"	"	"
26	0.78	0.30	0.58	0.011	0.003	"	0.0006	"	"	0.0005
79	0.79	0.27	1.01	0.011	0.004	"	0.0007	"	"	0.03
36	0.71	0.29	1.51	0.013	0.007	0.06	0.0015	0.001	"	0.0005
44	0.74	1.07	0.59	0.012	0.004	0.05	0.0005	0.001	0.014	"
39	0.71	1.09	1.01	0.012	0.007	0.06	0.0015	0.002	0.009	"
47	0.69	1.08	1.50	0.011	0.003	0.01	0.0018	0.001	0.01	"
78	0.65	2.00	0.58	0.012	0.002	"	0.0007	0.002	"	0.02
75	0.68	1.83	1.03	0.012	0.003	"	0.002	0.01	"	0.01
74	0.70	1.86	1.49	0.013	0.006	"	0.0007	0.002	"	0.01

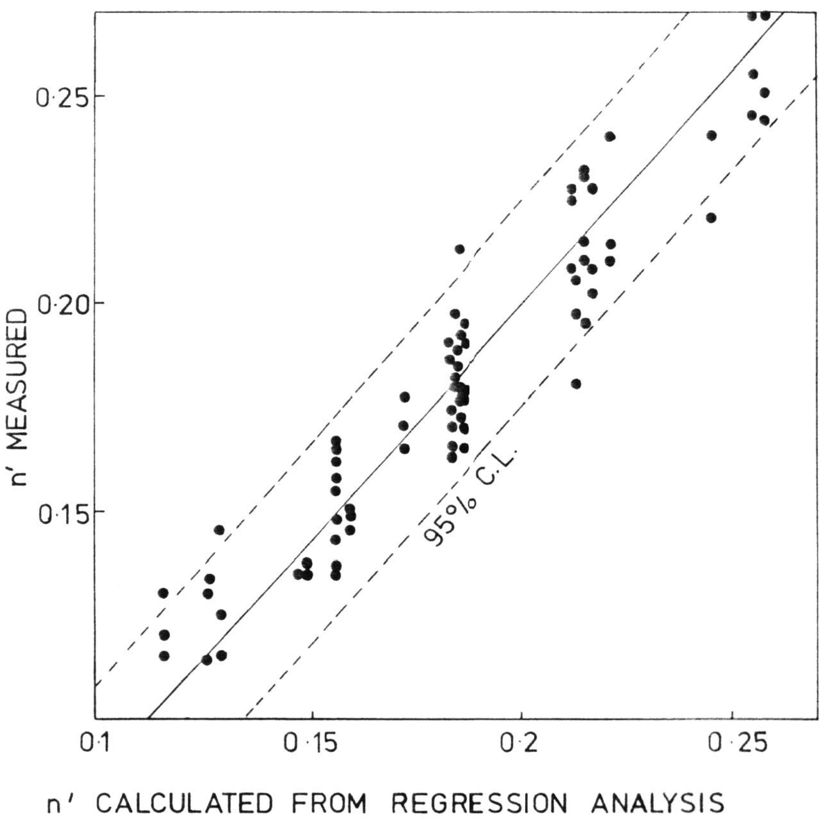

Figure 1 Measured and Calculated Values of the Cyclic Strain Hardening Exponent

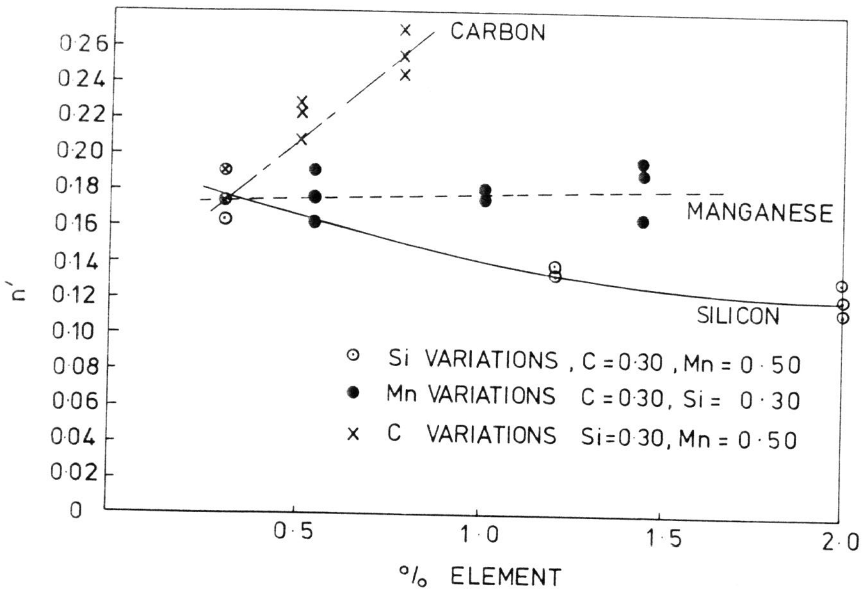

Figure 2 Effect of Composition on the Cyclic Strain Hardening Exponent