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Fatigue performance and cyclic softening of F82H, a ferritic-martensitic steel

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Abstract

The room temperature fatigue performance of F82H has been examined. The fatigue life was determined in a series of strain-controlled tests where the stress level was monitored as a function of the number of accrued cycles. Fatigue lives in the range of 10^3 to 10^6 cycles to failure were examined. The fatigue performance was found to be controlled primarily by the elastic strain range over most of the range of fatigue lives examined. Only at low fatigue lives did the plastic strain range contribute to the response. However, when the significant plastic strain did contribute, the material showed a tendency to cyclically soften. That is, the load carrying capability of the material degrades with accumulated fatigue cycles. The overall fatigue performance of the F82H alloy was found to be similar to other advanced martensitic steels, but lower than more common low alloy steels which posses lower yield strengths.

1. Introduction

Ferritic steels are of high interest for application as structural materials in advance fusion systems. These materials have exhibited an ability to resist the effects of irradiation to very high doses at irradiation temperatures above about 400°C [1]. They are very resistant to void swelling and loss of fracture resistance as tested both by fracture toughness and by Charpy impact tests after doses as high as 200 dpa. The irradiation performance at lower temperatures is also good, though the materials are somewhat more prone to the loss of ductility through the irradiation-induced embrittlement process.

The structural and irradiation performance of the ferritic-martensitic class of these alloys (e.g. modified 9Cr-1Mo and HT-9) have particularly appealing properties which are largely based on the relatively complicated microstructure obtained through alloying and heat treatment. This class of alloys has particularly good strength properties with adequate ductility [2,3]. Much of this performance is based on high dislocation densities and a fine, well dispersed precipitate distribution. These alloys, however, are prone to softening during cyclic loading [4-7].

Based on the success of other ferritic-martensitic alloys, the F82H alloy was developed to take account of the advances in understanding of the compositional and microstructural features which would optimize alloy performance for fusion structural materials applications. The present work is an examination of the room temperature fatigue response of this alloy with particular attention to the tendency for cyclic softening.

2. Experimental

Specimens of F82H ferritic-martensitic steel for fatigue testing were fabricated from a 8 mm plate. The plate composition is (wt%) 7.71Cr-2.1W-0.18V-0.04Ta-0.096C-0.003P-0.003S. The plate received at heat treatment of 1040°C for 37 min followed by 750°C for 60 min. The specimens were taken both parallel and perpendicular to the rolling direction. Specimen dimensions were based on a subsize specimen geometry widely used for irradiation exposure. This specimen has a 3.1 mm gauge diameter

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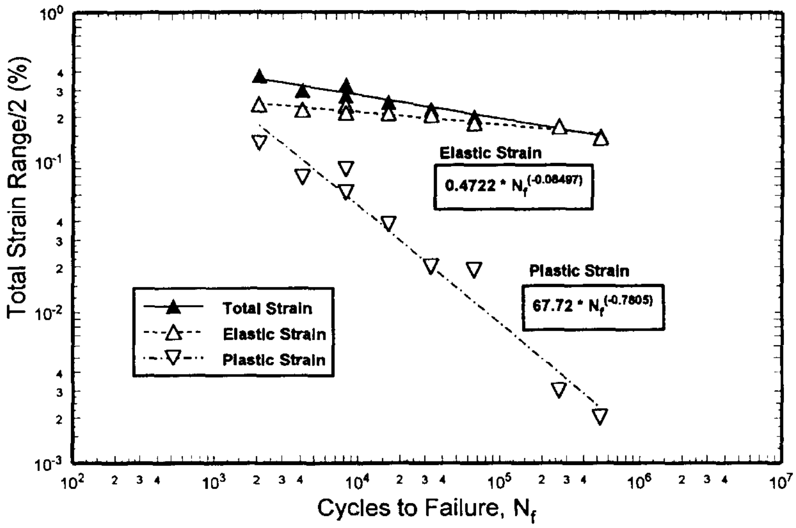

Fig. 1. Strain-life plot indicating the relative contributions of the elastic and plastic strain range to the failure life. The equations for the elastic and plastic strain ranges are indicated.

and a 6.32 mm uniform gauge length. This specimen geometry has been shown in other studies to provide reliable fatigue response, though the fatigue lives and the relative values of the elastic and plastic strain ranges may be somewhat different than standard ASTM specimen dimensions with gauge diameters of greater than or equal to 6.35 mm (0.25 in.) and uniform gauge lengths of 25.4 mm (1 in.) [8–10]. In particular, the smaller specimen size may result in slightly lower fatigue lives than the standard specimens under fixed fatigue testing conditions.

Fatigue tests were performed on a closed-loop servo-hydraulic mechanical loading stand. The test were run under strain range control such that the total strain range was held constant over the duration of the test. The stress required to maintained the applied strain range was monitored as a function of the number of loading cycles. All

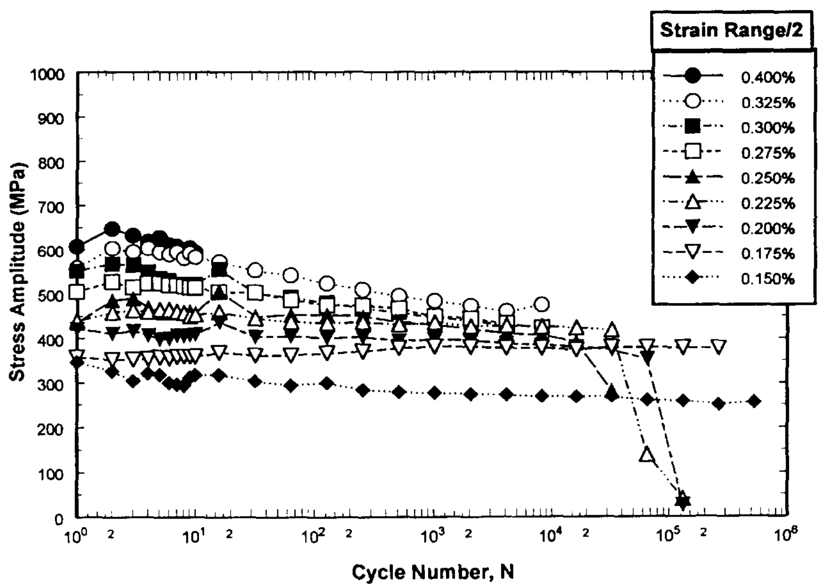

Fig. 2. The stress amplitudes at each strain range is shown as a function of the number of applied fatigue cycles.

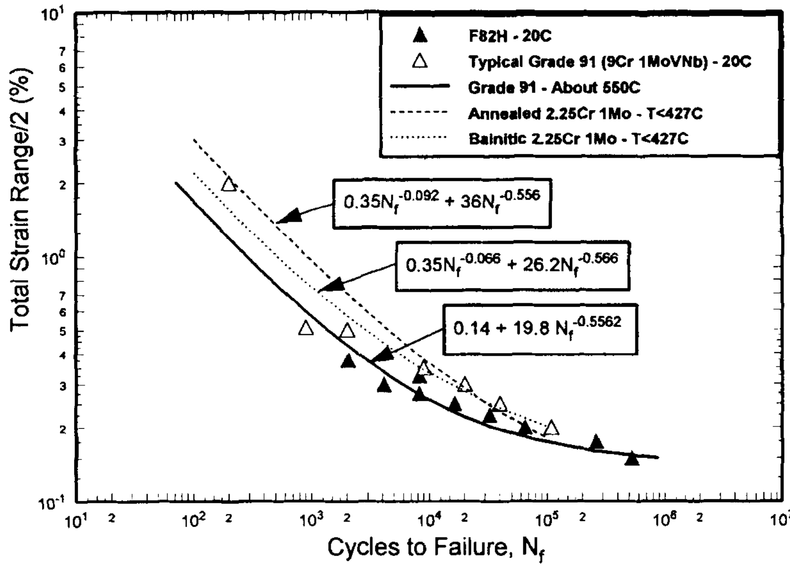

Fig. 3. The fatigue life trend curves are compared for the present F82H materials with fatigue response values for modified 9Cr-1MoNbV steel and annealed or bainitic 2.25Cr-1Mo steels.

tests were performed at room temperature in air at a cycle frequency of 1 Hz.

3. Results

The number of cycles to failure, N_f, is plotted against half the total strain range, $\Delta\epsilon_{tot}/2$, in Fig. 1. In addition, contributions of the elastic strain range, $\Delta\epsilon_{elastic}/2$, and the plastic strain range, $\Delta\epsilon_{plastic}/2$, are shown in the figure. The value plotted were taken from the hysteresis loop response at half the failure life. The figure indicates that, over the range of lives studied, the elastic strain was the dominant portion of the total strain range. The plastic strain was significant only for the test conditions which resulted in the lowest fatigue lives. From the data, it is apparent that the fatigue transition life, that is the point where the elastic and plastic strain ranges are equivalent, $\Delta\epsilon_{elastic} = \Delta\epsilon_{plastic}$, occurs at fatigue lives of around 10^3 cycles to failure. The transition life is usually assume to

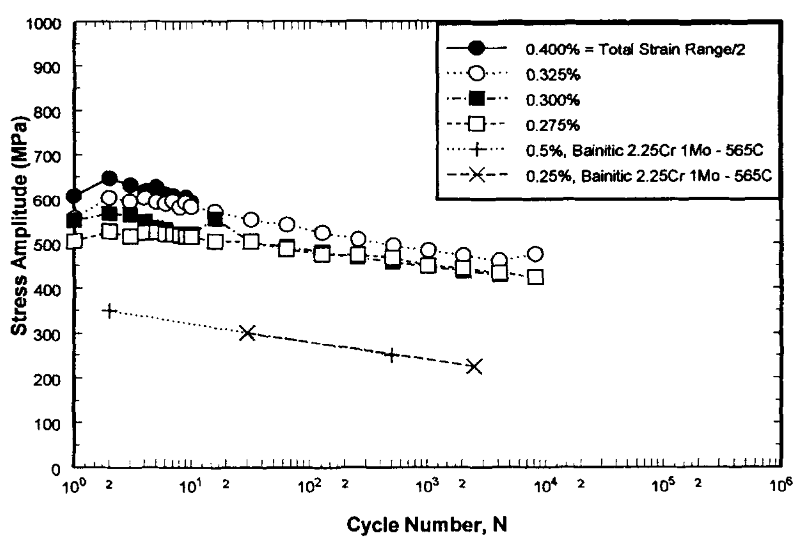

Fig. 4. Comparison of cyclic softening trends for F82H at room temperature and 2.25Cr-1Mo steel in the bainitic form at 565°C.

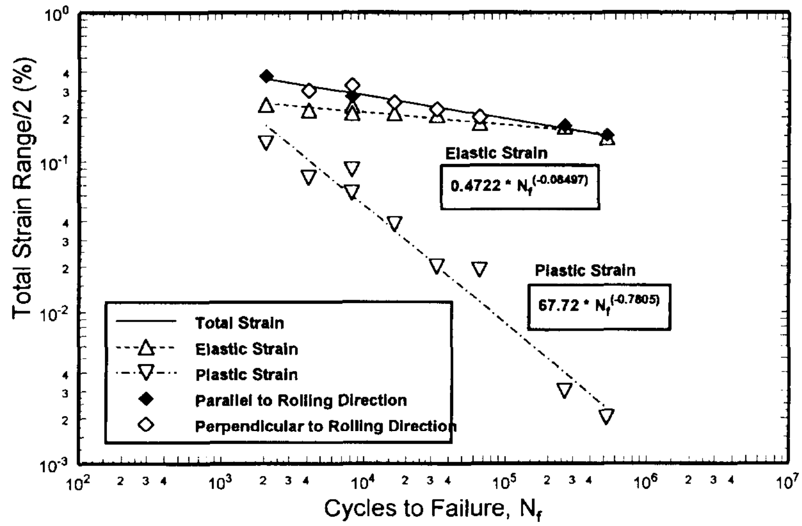

Fig. 5. The effect of specimen orientation with respect to rolling direction is indicated. Note that only the total strain range symbols are marked for rolling direction. The elastic and plastic strain range symbols are associated with the total strain range symbol directly above them.

delineate the low cycle fatigue (LCF) behavior where the plastic strain dominates and the high cycle fatigue (HCF) life where the elastic response dominates.

The fatigue response can be well represented by the well known strain-life equation:

$$\frac{\Delta \epsilon_{\text{tot}}}{2} = \frac{\sigma_f'}{E}(N_f)^b + \epsilon_f'(N_f)^c$$
$$= 0.47(N_f)^{-0.085} + 67.7(N_f)^{-0.78}$$

where E is the elastic modulus, σ_f' is the fatigue strength coefficient, and ϵ_f' is the fatigue strain coefficient. The values of the exponents $b = -0.085$ and $c = -0.78$ are within typical ranges, though the value for c is somewhat higher than 'universal' values of -0.5 proposed by Coffin or -0.6 proposed by Manson, and typical values on comparable alloys of around -0.55 (see below). In the present work, the plastic strain ranges were typically small, resulting is some degree of uncertainty in the precise value.

Fig. 2 shows the stress response versus the number of accrued fatigue cycles. The maximum stress or stress amplitude, required to attain the fixed strain level is plotted over the duration of the fatigue life. For the tests at the lowest fatigue lives, that is, the largest plastic strain ranges, there is a clear indication of cyclic softening, particularly following the initial loading cycle. This drop in strength is an indication of loss in load carrying capability following extended cycling. The cyclic softening behavior is not apparent at the lower strain ranges where the plastic strain becomes a vanishing small fraction of the total strain. In those cases, the stress response is virtually unaffected by the accrued numbers of loading cycles.

4. Discussion

4.1. Fatigue life

The room temperature fatigue performance of the F82H alloy is similar to that reported for the modified 9Cr–1MoVNb alloy class [2]. The strain range vs. fatigue life response for the F82H alloy is compared to the median room temperature fatigue lives and the average 550°C fatigue trend curve of the modified 9Cr–1MoVNb alloy [10] in Fig. 3. The room temperature response for the two alloys is similar. The slightly lower lives of the F82H may, in part, be due to specimen size effects. However, the points plotted for room temperature fatigue response of the modified 9Cr–1MoVNb alloy class are representative of the midpoint lives.

The fatigue life attributes of the 2.25Cr–1Mo in both the annealed condition and in the bainitic (normalized or normalized and tempered) condition [11] are also indicated in Fig. 3. Both the annealed and bainitic forms show superior fatigue life to F82H and to the 9Cr–1MoVNb class of materials. This trend is typical in the low cycle fatigue regime where lower strength and higher ductility provide better LCF resistance.

It is noteworthy that while the fatigue performance of the modified 9Cr–1MoVNb alloy class is indicated to have a fatigue endurance limit around a strain range of $\Delta\epsilon_{tot}/2 = 0.14\%$, the F82H and the 2.25Cr–1Mo alloys provide no indication of such a limit over the range of conditions tested.

4.2. Cyclic softening

The tendency for cyclic softening is associated primarily with the plastic strain range. Since the elastic strain dominates over most of the conditions tested here (see Fig. 1), the full effect of cyclic softening is not evident. The degree of softening in the materials conditions tested at strain levels at and above $\Delta\epsilon_{tot}/2 \geq 0.250\%$ are shown in Fig. 4 and compared to the cyclic softening phenomenon found in bainitic 2.25Cr–1Mo steels [12]. Fig. 4 contains a plot of the experimentally determined cyclic softening response of the bainitic 2.25Cr–1Mo material tested at 565°C [12]. Trend lines for two strain ranges, $\Delta\epsilon_{tot}/2 = 0.500$ and 0.250%, are shown. The similarity in the softening slopes should be noted despite the relatively large differences in the stress levels to produce similar levels of strain. This cyclic softening behavior has been shown to have a dramatic effect on the strength properties of these steels, particularly at elevated temperature. In particular, the creep strength of the bainitic 2.25Cr–1Mo steel was drastically reduced subsequent to only a few cycles of fatigue loading [13].

4.3. Other effects

It was noted that specimens were obtained both perpendicular and parallel to the rolling direction in the present F82H material. The fatigue response, however, seems not to be affected by the orientation with respect to the rolling direction. The data for the strain-life response are re-plotted in Fig. 5. There is no apparent difference in the fatigue lives or the relative contributions of the elastic and plastic strain response with specimen orientation. This is an indication of the uniformity of the as-rolled microstructure.

The potential influence of specimen size on fatigue life and cyclic stress response has been mentioned above. It is useful to note that in most cases where sub-sized specimens have been employed, the differences in fatigue performance compared to standard size specimens is small, but does tend to result in the same or slightly lower lives at fixed fatigue conditions, i.e., fixed strain ranges.

5. Conclusions

The room temperature fatigue response of F82H has been examined in a number of strain controlled cyclic loading tests. The following conclusions can be drawn from the results of those tests.

(1) The fatigue performance of the F82H is dominated by the elastic strain range over most of the useful fatigue life regime. The fatigue transition life is at or below one thousand cycles.

(2) At low lives where the plastic strain contributes most, the alloy is prone to softening with cycling, that is cyclic softening. This effect is evident by the constantly dropping stress levels which are required to maintain a fixed strain level. This loss of load carrying capability has serious consequences for design requirements.

(3) The fatigue response is close to other advanced ferritic-martensitic alloys such as the modified 9Cr–1Mo steels.

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