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Influence of Porosity on Fatigue Cumulative Damage of Sintered Iron

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Fatigue represents a common mechanical condition during service for materials used in structural components. This type of loading becomes particularly critical when alternating stress amplitude may be expected to vary, or change, in some way during the service life. Such variations and changes in load amplitude make the direct use of standard *S-N* curves inapplicable, because these curves are developed and presented for constant stress amplitude operation. In the present paper, results of cumulative damage under fatigue of porous materials are reported. The specimens used were produced by compacting and sintering iron powder. Their as-sintered porosity contents were P_0 = 4.1 and 12.4%. Uniaxial fatigue tests (tensile-compression) were carried out at room temperature on a hydraulic testing machine.

Keywords cumulative damage, fatigue, porosity

1. Introduction

The fatigue strength of powder metallurgy (P/M) materials is much lower than that of similar pore-free materials, so there is reluctance to use porous materials for the more responsible components. The prevailing opinion is that the market demand for P/M materials would increase markedly if the problems of fatigue in these materials could be solved.

As a result, many research efforts on fatigue in sintered materials have been undertaken, and significant advances have been made toward understanding the fatigue behavior of these materials (Ref 1-9). It is well-established that the fatigue endurance limit (S_N) of porous materials decreases with increasing porosity and decreasing pore roundness.

While these efforts are of great importance, they cannot give a basis for a consistent use of P/M materials where highly reliable components are required and fatigue is known to be a major problem. Moreover, the stress amplitude experienced by a component may often vary during its service life. In this situation of variable-amplitude loading, the direct use of *S-N* curves is not possible, because these curves are developed under constant stress amplitude operation. The purpose of this study is to present the effect of applying several different stress amplitudes on the fatigue strength of sintered iron with two different porosities.

1.1 *Cumulative Damage Theories*

The basic concept of cumulative damage theories is that operation at any given cyclic stress amplitude greater than the endurance limit (S_N) will produce fatigue damage. In other words, the material properties are changed after accumulation of fatigue damage and a specimen actually exhibits a new and different *S-N* curve. This damage is a function of the number of cycles of operation at that stress amplitude, and also a function of the total number of cycles that would be required to produce failure of an undamaged specimen at that stress amplitude (Ref 10, 11). Many different cumulative damage theories have been proposed in order to determine fatigue damage caused by operation at any given stress level (Ref 11-14).

1.1.1 Linear Damage Accumulation Rule (Palmgren-Miner Rule)

This theory may be described by using the schematic *S-N* curve shown in Fig. 1. It has been proposed that fatigue fracture under stress σ_{ai} is a result of a linear accumulation of partial fatigue damage D_i, which is linearly proportional to the ratio of n_i to N_i:

$$D_i = \frac{n_i}{N_i},\ n_i \le N_i \qquad \text{(Eq 1)}$$

where n_i is the number of cycles of operation under this stress amplitude and N_i is the total number of cycles that would produce a failure at that stress level (Ref 11).

If the stress amplitude is changed, a new partial damage is calculated for this new amplitude level, and the appropriate N_i is taken from the *S-N* curve. Thus, operation over a spectrum of different stress levels results in a damage fraction D_i for each of

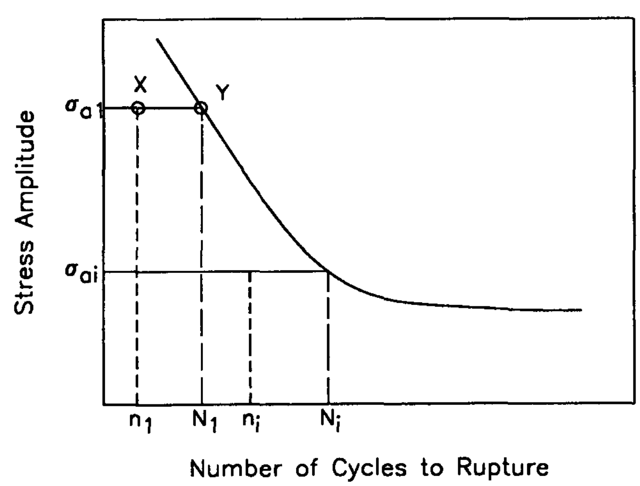

Fig. 1 Schematic of the *S-N* curve used in describing the Palmgren-Miner rule

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the stress levels in the spectrum. It is assumed that failure occurs if:

$$D_1 + D_2 + \ldots + D_{i-1} + D_i \geq 1 \qquad \text{(Eq 2)}$$

1.1.2 Henry Cumulative Damage Theory

The cumulative damage theory proposed by Henry (Ref 11, 14) is based on the fact that the *S-N* curve is shifted as fatigue damage takes place. It has been postulated that fatigue damage D_1 may be defined as the ratio between the reduction of the endurance limit and the original endurance limit of virgin material $S_{N,0}$; that is:

$$D_1 = \frac{S_{N,0} - S_{N,1}}{S_{N,0}} \qquad \text{(Eq 3)}$$

where $S_{N,1}$ is the endurance limit after damage. After some reasoning (see Ref 11), the new endurance limit after damage may be calculated by:

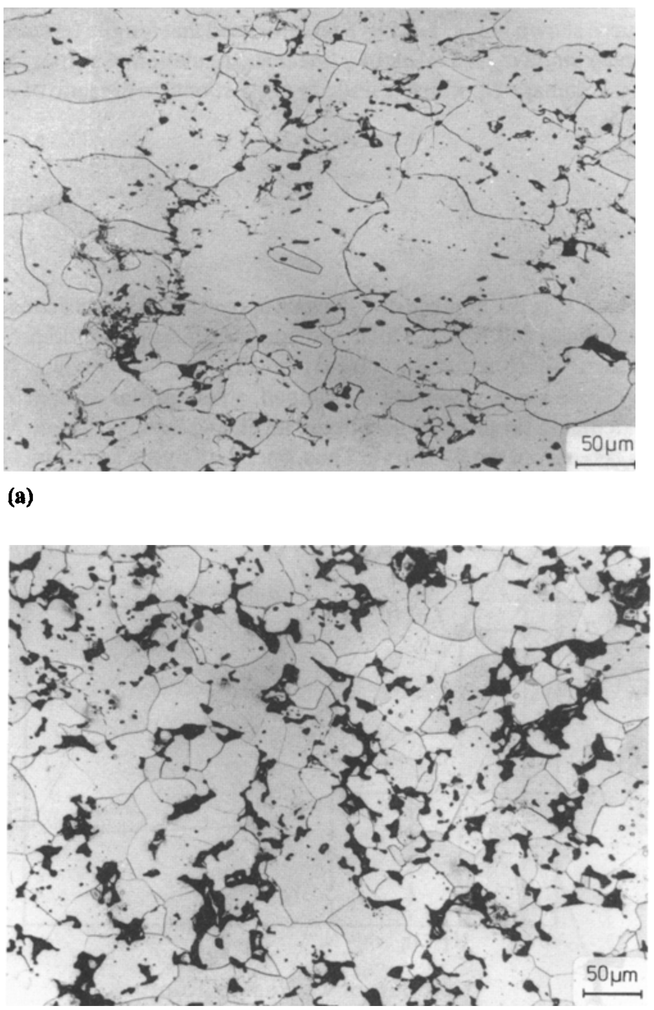

Fig. 2 Microstructures of iron. (a) $P_0 = 4.1\%$. (b) $P_0 = 12.4\%$

$$S_{N,1} = \frac{\sigma_{a1}\left(1 - \dfrac{n_1}{N_1}\right)}{\left(\dfrac{\sigma_{a1} - S_{N,0}}{S_{N,0}}\right) + \left(1 - \dfrac{n_1}{N_1}\right)} \qquad \text{(Eq 4)}$$

where n_1 is the number of cycles under stress amplitude σ_{a1} (point X in Fig. 1) and N_1 is the number of cycles to failure of virgin specimens (point Y in Fig. 1).

The complete, and modified, *S-N* curve at each damage level can be obtained by connecting with a straight line the calculated value of $S_{N,1}$ from Eq 4 at 2×10^6 cycles and σ_a, the ultimate tensile strength at 1 cycle.

2. Experimental Procedure

2.1 *Material and Specimens*

The raw material used in this investigation was Höganäs ASC 100.29 iron powder. Samples were made by mixing elemental powder with 0.5 wt% lubricant (zinc stearate). Figure 2 shows the microstructures of iron with both porosities, $P_0 = 4.1$ and 12.4%.

Fatigue specimens with a gage length of 10 mm, as shown in Fig. 3, were produced using a floating die tool. The compacting pressure was varied such that two levels of as-sintered porosities ($P_0 = 4.1$ and 12.4%) were produced. The specimen sinterization was carried out for 30 min at 1150 °C in an $80N_2$-$20H_2$ atmosphere.

2.2 *Apparatus and Conditions*

Experimental fatigue tests were carried out on a hydraulics testing machine, with stress control at room temperature. All specimens were subjected to an uniaxial tensile-compression load with a fatigue load ratio $R = -1$ at a frequency of 10 Hz. To develop each *S-N* curve, the test was run at constant stress amplitude until the specimen failed or the machine reached at least 2×10^6 cycles. Failure was defined as complete fracture, and the number of cycles to failure was noted as N_F. Runouts, or points for which fatigue failure was not observed during the test, are indicated by an arrow in the figures. Endurance limit S_N was determined by using the staircase (or up-and-down) method (Ref 11). For each porosity a population of at least 19 samples was used. Additionally, the standard deviation was calculated by using the method described in Ref 11, and assuming a logarithmic Gaussian distribution.

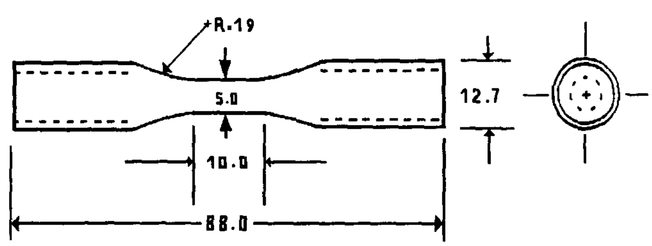

Fig. 3 Geometry of fatigue specimens. Dimensions are in millimeters.

A two-step test was used to determine fatigue damage. First, a specimen was subjected to a stress amplitude σ_{a1} ($\sigma_{a1} > S_N$) for n_1 cycles ($n_1 < N_{F1}$). Second, the same specimen was loaded under a stress amplitude smaller than its original endurance limit until failure took place or the machine reached at least 2 × 10^6 cycles.

3. Experimental Results

Figure 4 shows the *S-N* curves of iron with both porosities, P_0 = 4.1 and 12.4%. The *S-N* curves were obtained by drawing straight lines through the mean values (probability of survival P_S = 50%) of several stress levels. As expected, the curves shifted to a lower stress level, and the endurance limit decreased, with increasing porosity. The fatigue endurance limits were determined using the staircase method, and values of S_N = 59 ± 5 MPa for P_0 = 12.4% and S_N = 115 ± 9 MPa for P_0 = 4.1% were obtained.

In order to analyze the influence of fatigue damage, two-step tests were performed. The specimens of iron with both porosities were first subjected to a spectrum of nominal stress amplitudes, as summarized in Table 1. Subsequently, these specimens were cyclic loaded, each one under constant stress amplitude, until they failed or the machine reached at least 2 × 10^6 cycles.

Figures 5 and 6 show a comparison between experimental data and the fatigue behavior predicted by the theories proposed by Palmgren-Miner and Henry. Calculations made by using the linear damage rule (Palmgren-Miner) lead to a decrease in fatigue endurance limit after damage of only 3% (S_{N1} = 111.6 MPa), while the theory proposed by Henry (Eq 2) leads to a reduction of 8.7% (S_{N1} = 105 MPa) for iron with P_0 = 4.1%. Similar results were obtained for iron with P_0 = 12.4%. In the second-step test, all damaged specimens with P_0 = 4.1% failed before reaching 2 × 10^6 cycles, when subject to stress amplitudes $\sigma_a \geq$ 100 MPa. Under σ_a = 98 MPa, just one specimen ran out. Only two specimens with P_0 = 12.4% ran out under σ_a = 40 or 44 MPa. All specimens failed before reaching 2 × 10^6 cycles when subject to stress amplitudes $\sigma_a \geq$ 46 MPa.

Table 1 Nominal stress amplitudes and number of cycles applied in the first step of the tests

Porosity, P_0, %	Stress amplitude, σ_{a1}, MPa	Number of cycles, n_1, under σ_{a1}
4.1	140	60 × 10^3
12.4	89	18.4 × 10^3

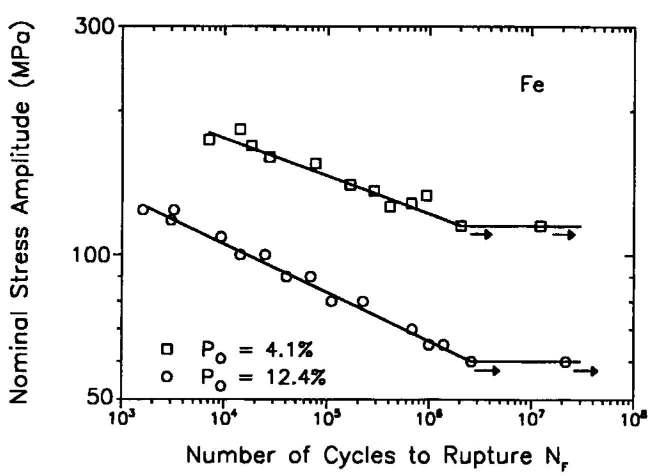

Fig. 4 *S-N* curves for iron with P_0 = 4.1 and 12.4%

4. Discussion

As expected, the experimental results showed that fatigue endurance limits decreased with increasing porosity. They were very similar to those found in the literature (Ref 2-9). It is well known that the decrease of endurance limit with porosity is due to a reduction in true load-bearing cross-sectional area,

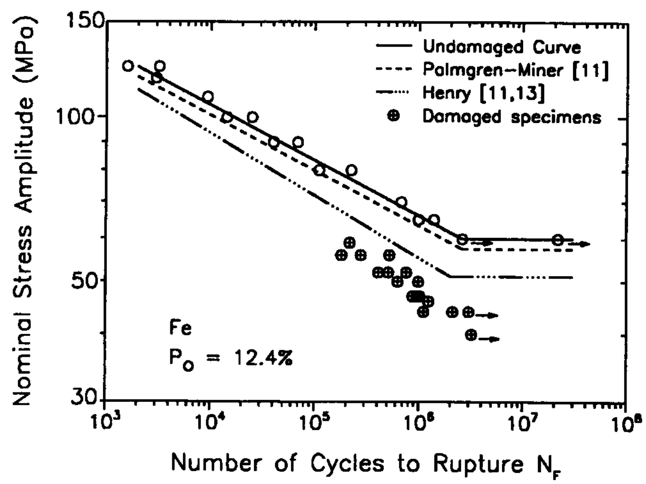

Fig. 5 Comparison of predicted fatigue behavior by Palmgren linear damage rule and Henry cumulative damage theory with experimental data for iron with P_0 = 12.4%. The open circles are the data points from Fig. 4.

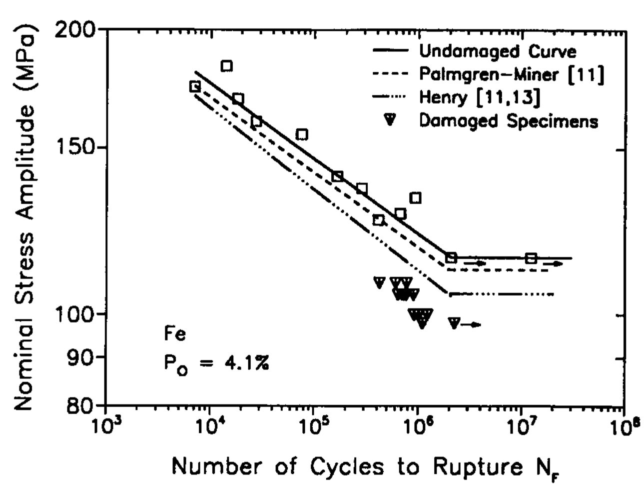

Fig. 6 Comparison of predicted fatigue behavior by Palmgren linear damage rule and Henry cumulative damage theory with experimental data for iron with P_0 = 4.1%. The open squares are the data points from Fig. 4.

and mainly due to the pores acting as an assemblage of small stress concentrators. Thus, some or all of the pores may act as crack precursors, and subsequently, those cracks can grow by a process of microvoid coalescence (Ref 15).

It was also observed that the fatigue strength of damaged specimens was remarkably smaller than the fatigue strength of the undamaged specimens, since cracks were nucleated during the first step of the test. In other words, a fraction of the specimen was consumed during the first cycles. Because of the presence of pores, nucleation of cracks in P/M materials takes place earlier and more aggressively than in similar pore-free materials. Thus, when subjected to a cyclic stress that was smaller than the original fatigue endurance limit, during the second step of the test, the crack initiation phase of the process was suppressed, and fatigue failure took place only due to crack propagation. The remaining life was relatively short and failure occurred before the machine reached 2×10^6 cycles.

Neither cumulative damage theory properly predicts the observed decrease in fatigue strength during the second step of the test. Certain significant influences are unaccounted for, and failure prediction errors may be expected. Perhaps the most significant shortcomings of both models are that they do not recognize the influence of the order of application of several stress levels or the processing history of the specimens. These discrepancies become more important when pores are present in P/M materials. Cyclic stress applied early, then relaxed, result in a residual stress field in the vicinity of the pores, and later application of lower (or higher) cyclic stresses produces less (or more) damage, depending on whether the induced residual stresses are tension or compression.

Further work will be necessary to investigate damage accumulation during fatigue. Several fatigue tests in different life regions have to be carried out, and a statistical description of *S-N* curves is of fundamental importance. In addition, other approaches will have to be used to overcome the weaknesses stated above. Nowadays a probabilistic approach to modeling fatigue process is used (Ref 10, 16-18). According to this approach, fatigue accumulation takes place dynamically, whose evolution in time is represented by a stochastic vector process (Ref 17).

5. Conclusions

The experimental results of this investigation can be summarized as follows:

- Fatigue endurance limits decreased with increasing porosity, and the values were very similar to those found in the literature.
- The experimental results of fatigue strength were smaller than those predicted by theoretical models. Both models discussed here have shortcomings.
- Further work will be necessary to investigate damage accumulation during fatigue, and to get statistically reliable results.
- It is necessary to use a probabilistic approach to modeling fatigue process and evolution of damage in time.

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