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SPRINGFIELDS NUCLEAR POWER DEVELOPMENT LABORATORIES

AN ASSESSMENT OF THE LINEAR DAMAGE SUMMATION METHOD FOR CREEP-FATIGUE FAILURE WITH REFERENCE TO A CAST OF TYPE 316 STAINLESS STEEL TESTED AT 570°C

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1. Introduction

Over recent years many studies have investigated the elevated temperature hold period cycling behaviour of austenitic stainless steels, principally types 316 and 304 steel. The results of these studies indicate that the introduction of a tensile hold period reduces the fatigue life from that in continuous cycling tests. However, for nominally constant test conditions i.e. applied strain range, hold time and material the extent of the life reduction varies considerably depending on the particular cast of stainless steel and test temperature. This variability in material response leads to considerable difficulties in the extrapolation of short term data for the formulation and/or verification of design codes. With this in mind programmes of work have been initiated to test a variety of casts of type 316 stainless steel over a range of test temperatures with a view to (a) quantifying the extent of the creep-fatigue interaction phenomenon and (b) carrying out mechanistic studies to define the rate controlling failure parameters viz creep or fatigue damage in order to provide a confident basis for data extrapolation. This paper presents preliminary results from the programme for hold period tests on a cast BQ of type 316 stainless steel at 570°C. These results are used to assess the validity of the linear damage summation approach commonly used for the prediction of creep-fatigue failure. Details of the material specification and test methodology are given elsewhere.(1)

2. Experimental Results

Fig. 1 illustrates the effect of the imposition of a tensile hold period (between 0.25 and 10 hours), on fatigue life. Continuous cycling results are included for comparison. These results together indicate that an order of magnitude reduction in life occurs for hold periods of 3 hours and 2 hours at fatigue strain ranges of 2 and 0.6% respectively. The limited information available indicates that further life reduction does not occur as the hold period is extended by a factor of two to three.

3. Data Analysis

During the tensile hold period cycle, fatigue damage takes place by rapid reverse straining, whilst creep deformation occurs as a consequence of stress relaxation. In the following sections an assessment will be made of the relative contribution to failure of creep and fatigue damage fractions. Two methods of calculating creep damage will be used: one in terms of a time summation, the other a strain summation.

3a. Strain Summation Method for Creep Damage

This method involves calculation of the relaxation strain per cycle ε_R and normalising it with respect to the material ductility, D, here taken as the reduction in area in a creep or tensile test. The creep damage fraction per cycle ϕ_S is given as:

$$\phi_S = \frac{\varepsilon_R}{D} \qquad \ldots (1)$$

where $$\varepsilon_R = \frac{1}{E} (\sigma_{max} - \sigma_{min}) \qquad \ldots (2)$$

σ_{max} and σ_{min} are the stress levels at the beginning and end of the hold period. E is Young's modulus.

The total damage fraction at failure ϕ_{ST} is defined as:

$$\phi_{ST} = N_f \, \phi_S \qquad \ldots (3)$$

where N_f is the number of cycles to complete failure of the specimen in the hold period test.

In calculating ϕ_S account must be taken of the variation in strain rate during stress relaxation and the strain rate sensitivity of ductility. This latter relationship is illustrated for BQ material in Fig. 2. Analysis of the present hold period data indicates that stress relaxation is adequately described by the Conway equation(2):

$$\ln \left(\frac{\sigma_{max}}{\sigma} \right) = \frac{A}{1+m} \, t^{1+m} \qquad \ldots (4)$$

where σ is the stress level at a time t and A and m are constants. Strain rates during stress relaxation are in the range 10^{-4} to 10^{-9} s^{-1}.
Equations (2, 3 and 4) in conjunction with the ductility data of Fig. 2 have been used to compute the strain rate normalised creep strain damage parameter ϕ_S.

3b. Time Summation Method for Creep Damage

In the time summation method the creep damage fraction per cycle during stress relaxation is defined as:

$$\phi_t = \sum_{0}^{t_{dwell}} \frac{\Delta t}{T_f}$$

where t is the time spent at a stress level σ and T_f the time to failure in a uniaxial creep test at an applied stress level σ and t_{dwell} is the hold period duration.

Total fractional damage at failure ϕ_{tT} is given as:

$$\phi_{tT} = N_f \, \phi_t \qquad \ldots (5)$$

3c. Fatigue Damage

Finally fatigue damage fraction ϕ_F during hold period cycling tests is expressed as:

$$\phi_F = \frac{N_f}{N_o} \qquad \ldots (6)$$

where N_f and N_0 are the number of cycles to failure in a hold period and continuous cycling test at the same strain range.

Now if a linear damage summation of creep and fatigue damage describes failure during a hold period test, failure occurs when the sum of the creep and fatigue damage fractions is unity. The creep component of the summation can be calculated in terms of either time fraction or strain fraction and the failure criterion is indicated below:

$$\phi_F + \phi_{tT} = 1 \qquad \ldots (7a)$$

$$\phi_F + \phi_{ST} = 1 \qquad \ldots (7b)$$

4. Assessment of Damage Summation Methods

Fig. 3 is a plot of fatigue damage fraction against fractional creep damage, defined in terms of time summation ϕ_{tT}. Line A is the failure locus for a linear damage summation of unity. Note the vast spread in the data with points lying above and below the line. In Fig. 4, fractional fatigue damage is plotted against creep damage fraction in terms of strain summation ϕ_{ST}. The majority of the data fall below the linear damage failure line whilst the data for strain levels of 0.6 and 0.76% lie close to the line. Clearly the linear damage summation approach in terms of strain or time does not describe these data. Furthermore, the damage summation method based on a time and strain summation basis for creep damage are incompatible. Test conditions giving rise to a high damage value by the time fraction method, equation 7a, (high strain ranges) produce a low damage value using the creep summation method, equation 7b. This trend is reversed at low strain ranges. This point is clearly illustrated in Table 1.

Table 1

Strain Range %	Hold Time hours	ϕ_F	ϕ_{tT}	ϕ_{ST}
1.85	3	0.16	1.49	0.16
0.60	5	0.10	0.19	1.02

At the lower strain range, failure occurs when the creep damage fraction in terms of strain is unity and only 0.19 using the time summation approach i.e. a difference of a factor five. (This factor would increase with extended hold time). This highlights the discrepancy between the approaches.

When the data are considered in terms of fractional creep strain damage at failure, ϕ_{ST}, against applied fatigue strain range, a consistent trend emerges which throws light on the failure mechanism occurring in these tests. This is shown in Fig. 5. Here it will be noted that the fraction of exhausted creep rupture ductility at failure increases as the applied strain range is decreased. For a strain range of 0.6% and a hold time of 5 hours, total ductility exhaustion has occurred and failure by a creep mechanism is indicated. This is consistent with fractography which revealed a totally intergranular failure and an absence of fatigue striations. This observation is similar to that in low strain level hold period tests in type 316 stainless steel(3) and ferritic steels(4,5). Note from Table 1 that the damage summation value of $\phi_F + \phi_{ST} = 1.12$, which is in reasonable agreement with the linear summation value of 1, equation 7b. This agreement, however, is not a verification of the linear damage summation method but an affirmation of a previous postulation that from a failure mechanism point of view, a damage summation of unity can only occur when failure is dominated by one of the two possible fracture modes.(6) For higher strain levels, where only a fraction of the material ductility is exhausted, failure occurs by an interaction between the surface nucleated fatigue crack and intergranular creep cavitation.(1) Here creep failure is accelerated by the fatigue crack tip stress/strain field.

5. General Discussion

The present results indicate that for a fatigue cycle containing a hold period at the maximum tensile strain, the mechanism of failure is a function of applied fatigue strain range for hold periods in excess of about one hour. At fatigue strain ranges in excess of 0.6%, failure occurs by the interaction between a surface fatigue crack and internal grain boundary creep cavitation. At a strain range of 0.6% failure is by a creep mechanism and occurs when the accumulated relaxation strain exhausts the material uniaxial creep ductility. This change to a creep dominated failure is a consequence of the relatively low ductility of the material i.e. 15% for strain rates less than 10^{-6} s^{-1}, Fig. 2. This implies that at lower strain levels, creep fracture develops more rapidly than surface fatigue crack nucleation and growth and hence a creep-fatigue interaction is suppressed. It should be noted that for a higher ductility cast of material the transition strain range from creep fatigue interaction failure to a creep dominated failure will be lower than the 0.6% level noted here and vice versa.

Consideration has been given to the validity of the linear damage summation approach to creep-fatigue failure for this material. This has conclusively demonstrated its inability to describe data from tests in which failure occurs by a true creep-fatigue interaction mechanism. However, when failure is dominated by the creep fracture process viz at low applied strain levels, failure has been shown to occur when the accumulated relaxation strain exhausts the material creep rupture ductility. For this reason, the fractional fatigue damage term of the linear damage summation approach Equation 5 is not important, but if taken into account will result in a fractional damage summation in excess of unity. It is worth emphasising here that a creep failure summation approach based on time to failure (equation 5) underestimates creep dominated failure life by a factor five on cycles to failure (Table 1) and is considered an inappropriate life prediction method.

6. Conclusions

1. The results of tensile hold period tests on a relatively low ductility cast of type 316 stainless steel have indicated that the failure mechanism changes from a creep-fatigue interaction failure to a creep dominated failure at low strain levels.

2. An assessment of the linear damage summation approach for failure prediction indicates that it is inappropriate for creep-fatigue interaction failures. For creep dominated fracture,failure occurs when the accumulation relaxation strain exhausts the material ductility i.e. $N_f \varepsilon_R = D$. The failure criterion based on a creep summation in terms of time to fracture underestimates life.

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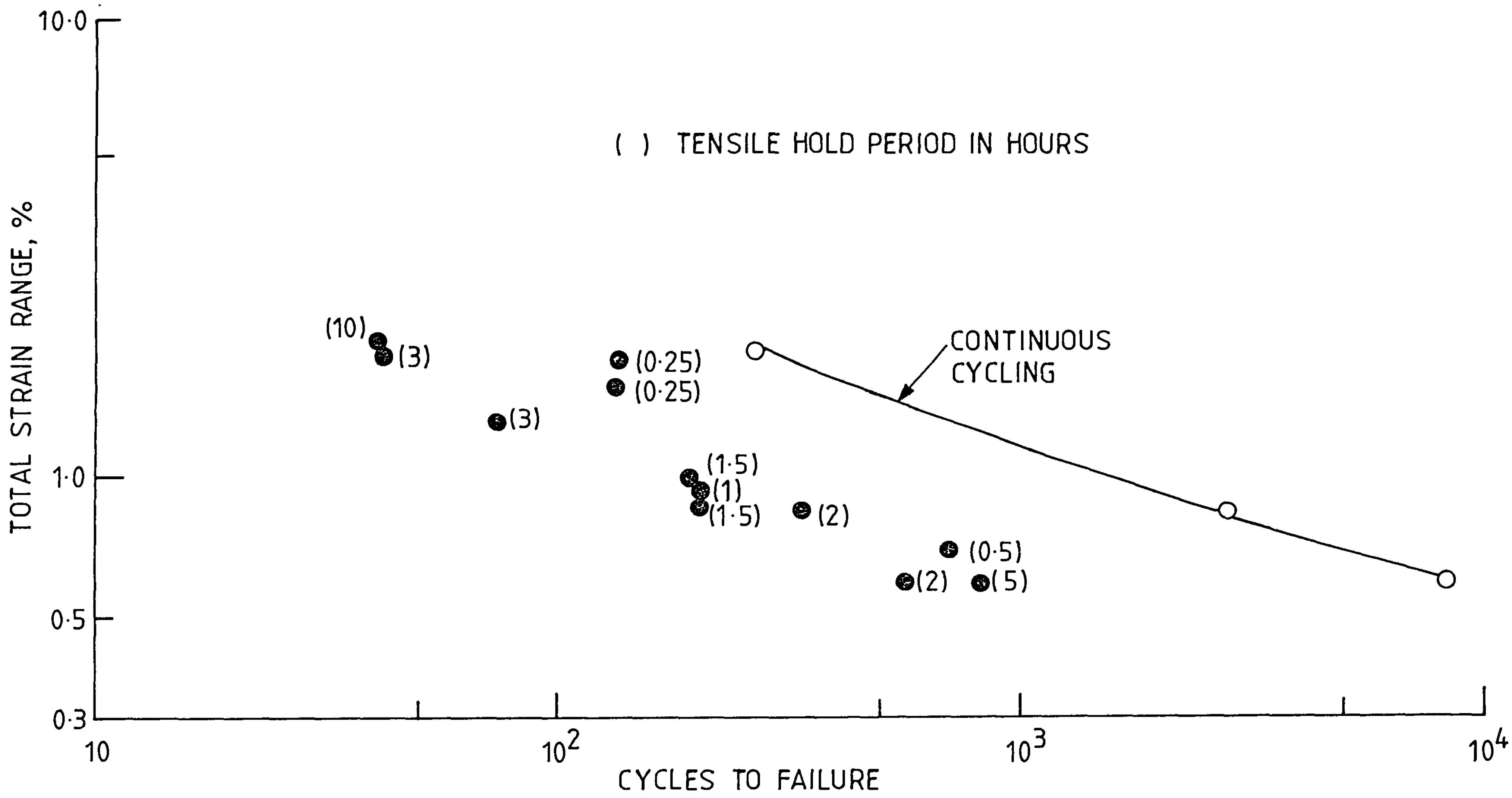

FIG.1. EFFECT OF TENSILE HOLD PERIOD ON FATIGUE LIFE OF CAST BQ TYPE 316 STAINLESS STEEL AT 570°C

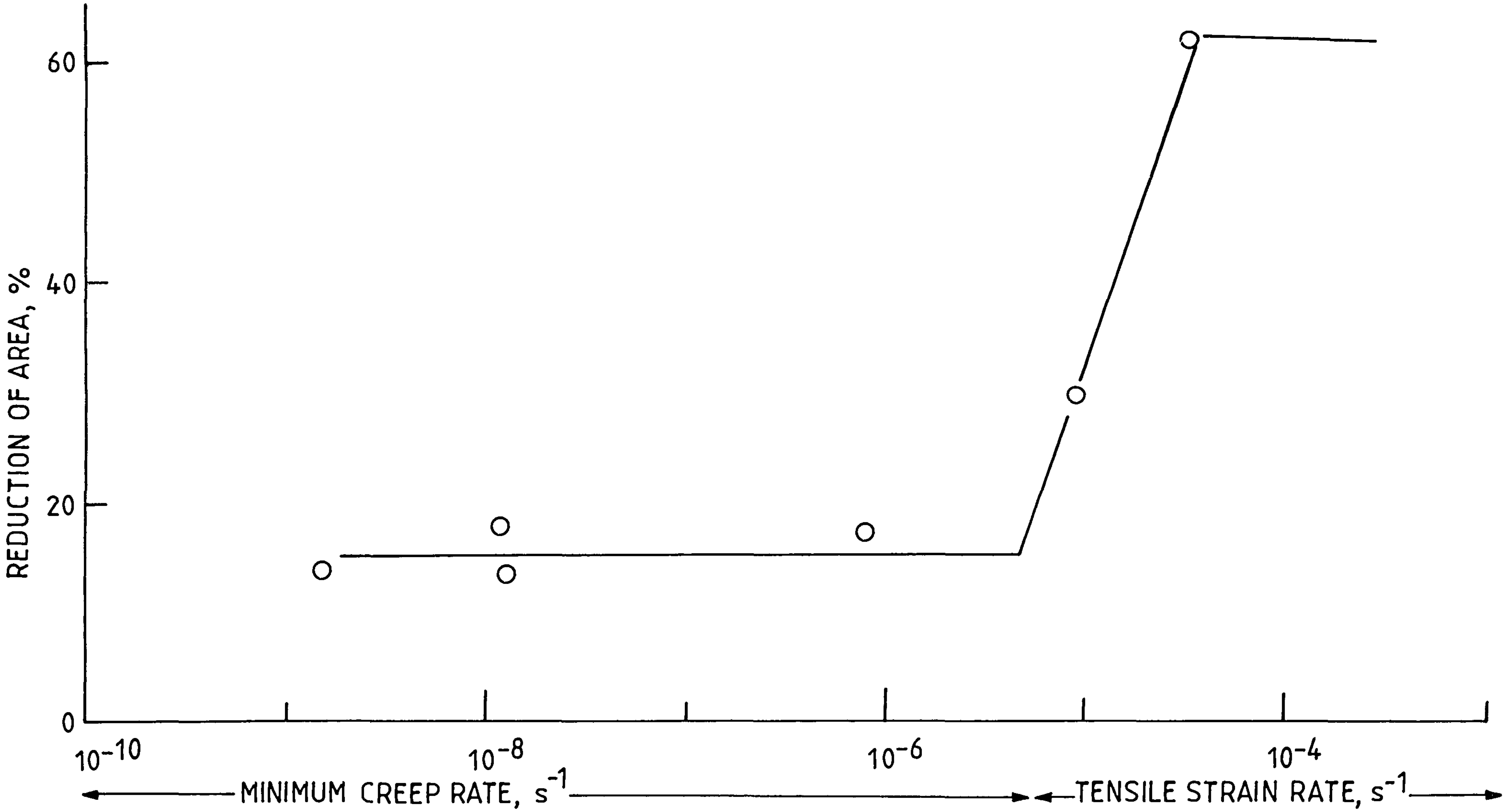

FIG. 2. DUCTILITY AS A FUNCTION OF STRAIN RATE FOR BQ MATERIAL

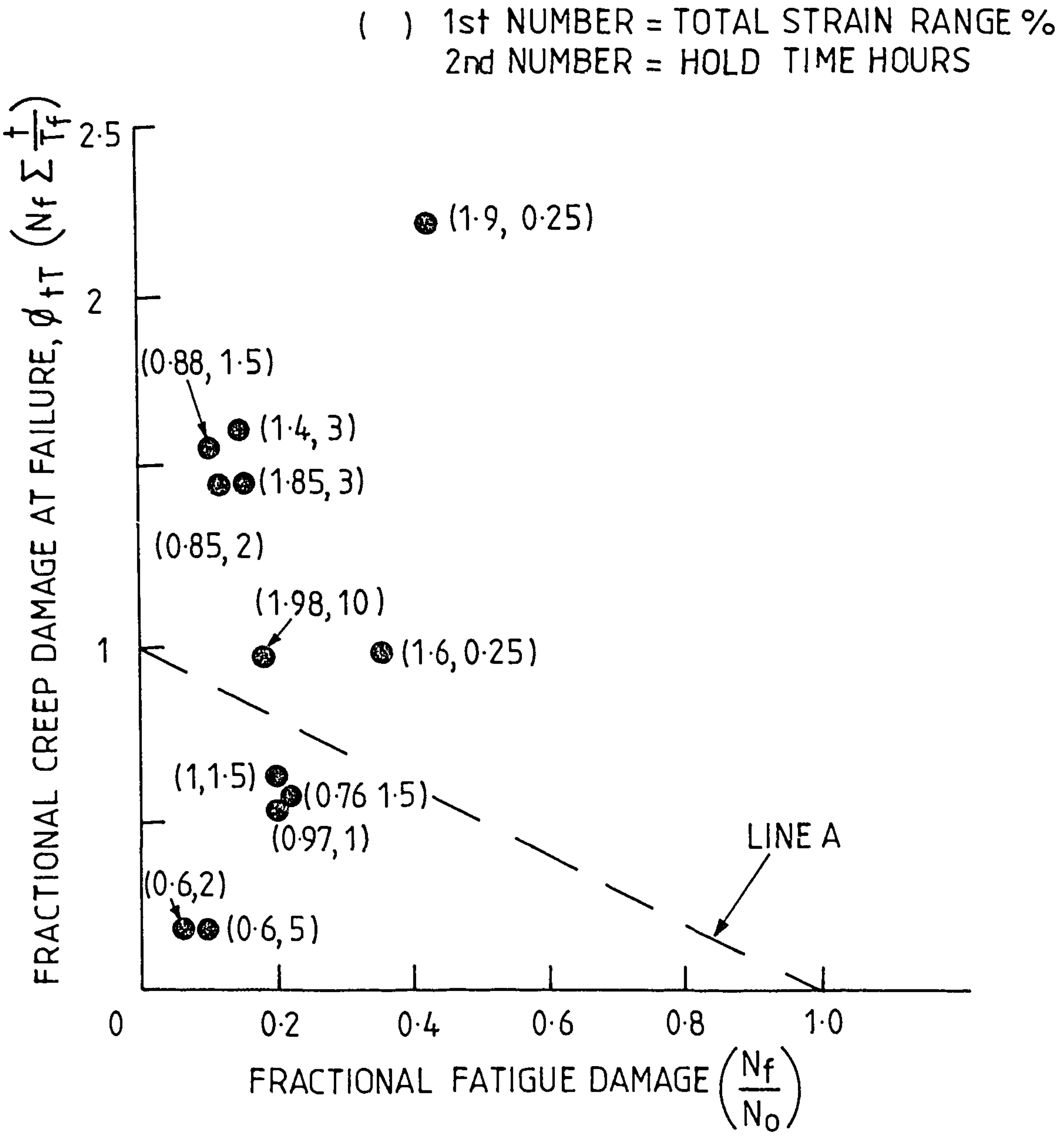

FIG. 3. FRACTIONAL FATIGUE DAMAGE AGAINST FRACTIONAL CREEP DAMAGE FOR TENSILE HOLD PERIOD CYCLING TESTS

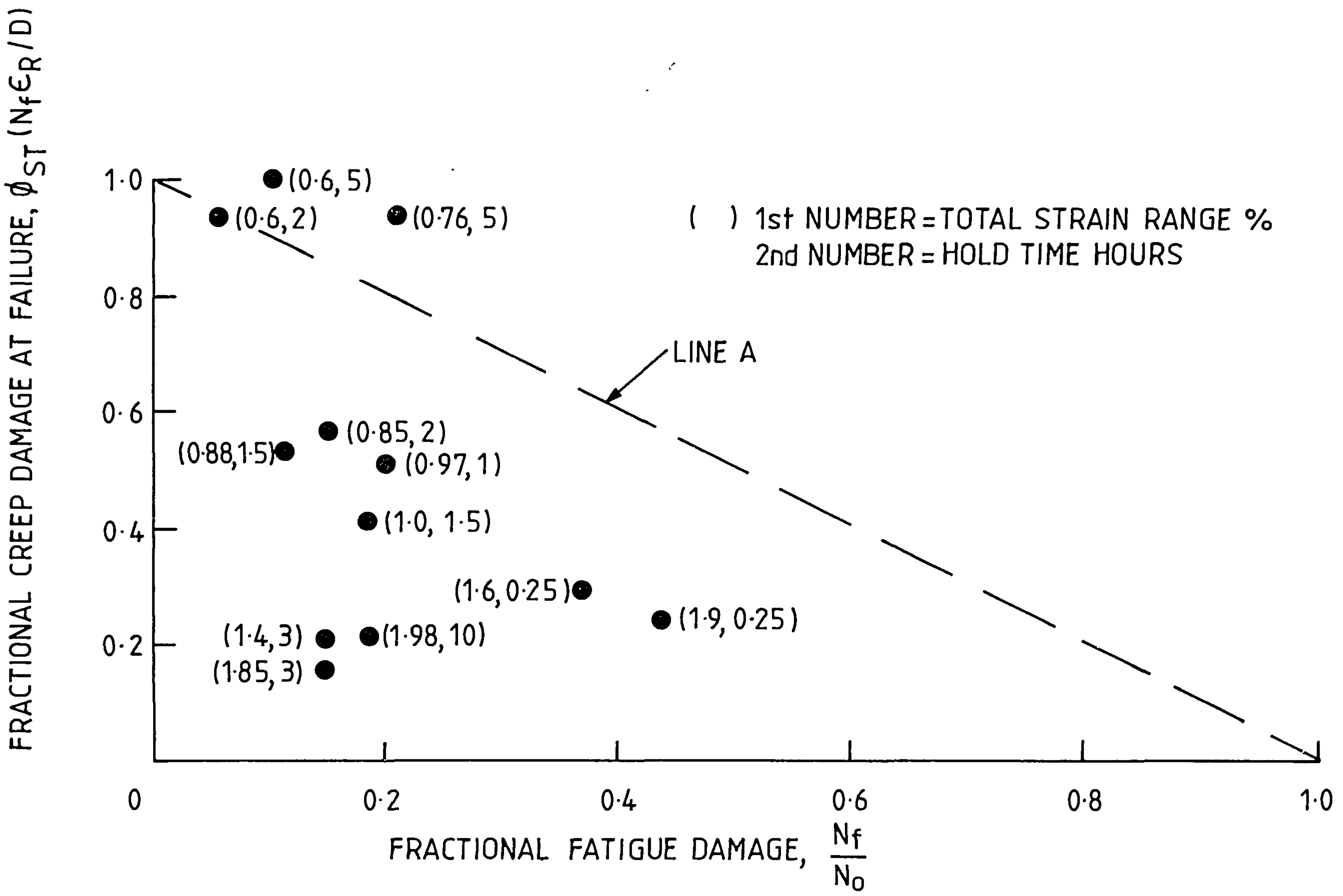

FIG. 4. PLOT OF FRACTIONAL FATIGUE DAMAGE AGAINST FRACTIONAL CREEP DAMAGE FOR TENSILE HOLD PERIOD CYCLING TESTS

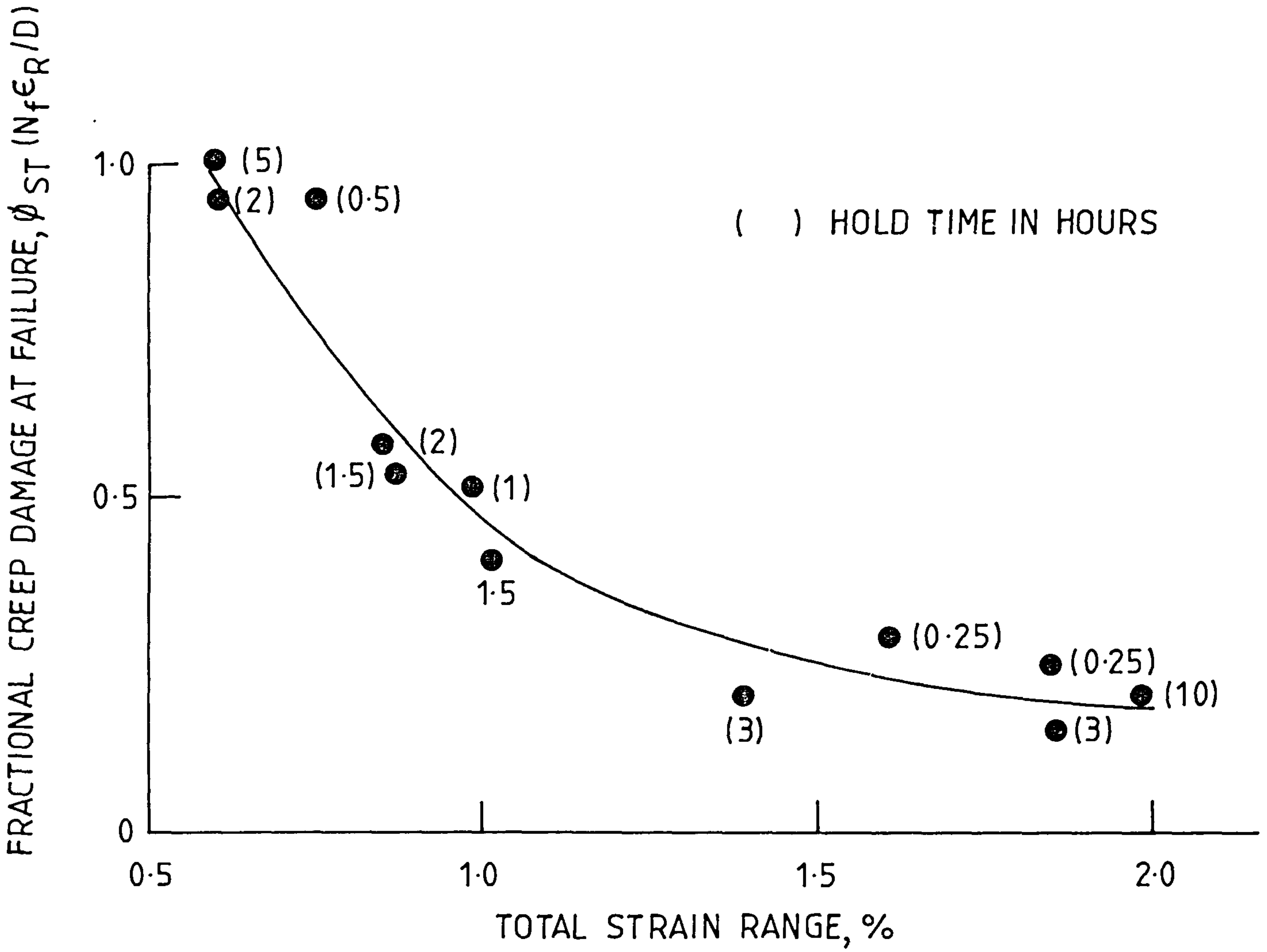

FIG. 5. FRACTIONAL CREEP DAMAGE AS A FUNCTION OF FATIGUE STRAIN RANGE FOR TENSILE HOLD PERIOD CYCLING TESTS