COMPARISON OF LOW-CYCLE FATIGUE DATA OF 2¼%CrMo STEELS

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ABSTRACT

Data files have been produced on international strain-controlled fatigue information available for 2¼%CrMo steels; data assessment from these files is treated in three categories viz: annealed and isothermally annealed 2¼%Cr1%Mo steel; normalised and tempered and quenched and tempered 2¼%Cr1%Mo steel; and 2¼%CrMo variants. The available data have been considered generally in terms of total strain range vs. cycles to failure (N_f), tensile stress at $N_f/2$ vs. cycles to failure and time to failure vs. cycles to failure. Where possible the continuous cycling data have been statistically analysed in terms of the elastic and plastic strain components and cycles to failure to yield best-fit equations over defined temperature (T) regimes viz: $T \leq 427^oC$, $427^oC < T \leq 550^oC$ and $550^oC < T \leq 600^oC$. The behaviour of the steels within the various classifications is discussed.

1. INTRODUCTION

The purpose of this paper is to present an analysis of available strain-controlled low-cycle fatigue data relevant to 2¼%CrMo steels in the various heat treated forms permitted by national and international specifications. It is important to determine the fatigue behaviour as clearly as possible since these steels are of interest in the design of European fast reactor steam generators whose performance may need to be assessed in terms of fatigue and/or creep-fatigue. A particular objective is to establish the effect of heat treatment on fatigue properties since the generic steel can be used in the annealed, isothermally annealed, normalised and tempered (N+T) or quenched and tempered (Q+T) conditions with the probability of additional stress relief heat treatments imposed during component fabrication.

The national and international specifications are general in respect of steel-making practice and allow use of electric arc, open hearth or basic oxygen processes to give a fully-killed product. Steel-making practice is not always available as background information to the compilation of strain-controlled fatigue data; however, where the process is known it is invariably by the electric arc route. The limited extent of data available for elevated temperature strain-controlled fatigue of 2¼%CrMo steels precludes a valid subdivision on the basis of cast-to-cast, product form or secondary heat treatment, consequently three major classifications have been defined using compositional and primary heat treatment criteria as annealed and isothermally annealed 2¼%Cr1%Mo steel; N+T and Q+T 2¼%Cr1%Mo steel; and N+T and Q+T 2¼%Cr1%Mo steels containing Nb or V. Where possible these classifications have been further subdivided for analytical purposes into three temperature (T) categories viz: $T \leq 427^oC$, $427^oC < T \leq 550^oC$ and $550^oC < T \leq 600^oC$.

For design purposes the major interest is centred on fatigue data presented in terms of total strain range vs. cycles to failure (N_f). Consequently these continuous cycling data are analysed in the paper with reference to the appropriate graphical representations in terms of the defined compositional and temperature range classifications. Examples from the data compilation covering tensile stress at $N_f/2$, and time to failure information are also presented in graphical form to substantiate more general observations on trends for these properties.

2. DATA SOURCES AND SELECTION CRITERIA

The data compilation addresses information available from smooth specimen, fully reversed uniaxial strain-controlled fatigue and creep-fatigue tests on wrought steel generally to a maximum number of cycles to failure of $\sim 10^5$ over an isothermal test temperature range from ambient to 600°C. International data taken from published sources were only compiled if available in tabular form ie: discrete numerical values of strain rate (or frequency), total strain range, plastic strain range at $N_f/2$ and number of cycles to failure for continuous cycling fatigue were taken as minimum data requirements. The majority of the information relates to tests conducted in air and consequently the effect of environment on fatigue is not examined in this paper.

Data using these selection criteria have been identified from the USA (1 to 9), Italy (10), Japan (11,12), Germany (13), Holland (14), France (15) and the UK (16). The data are available for 2¼%Cr1%Mo steel as annealed and isothermally annealed (1 to 9); N+T (8,9,10,15); Q+T (8,13); N+T plus stress relieved (11,12,16); and Q+T plus stress relieved (13,16). Data for Q+T Nb-stabilised 2¼%Cr1%Mo steel are found in (13,14); Q+T plus stress relieved Nb-stabilised 2¼%Cr1%Mo steel in (13) and N+T 2¼%Cr1%Mo¼%V steel in (9).

3. DATA ANALYSIS

The continuous cycling fatigue data for each heat treatment and compositional category have been analysed where possible over the temperature ranges $T < 427^oC$, $427^o < T < 550^oC$ and $550^o < T < 600^oC$. The temperature regimes limited by 427°C have been defined for compatibility with US analyses on the annealed variant of 2¼%Cr1%Mo steel (17). The highest temperature range has been included for completeness although it is recognised that this range may not be relevant to anticipated service conditions. Analytical subdivision of the data on the basis of strain rate within each temperature regime has not been attempted on the relatively sparse population whose strain rate deviates significantly from the majority range of 10^{-3} to 4×10^{-3}/s; all the analysed data relate to strain rates $\lesssim 4 \times 10^{-3}$/s. Best-fit equations between total strain range ($\Delta\varepsilon_T$) and cycles to failure have been derived from a Basquin/Coffin-Manson analysis of all valid data within a given heat treatment, compositional and test temperature category, resolving the total strain range into its elastic ($\Delta\varepsilon_E$) and plastic ($\Delta\varepsilon_P$) components:

$$\Delta\varepsilon_T = \Delta\varepsilon_E + \Delta\varepsilon_P$$

and $\Delta\varepsilon_T = AN_f^{-\alpha} + BN_f^{-\beta}$

where A, α, B, β are constants. This analytical approach retains a physical significance which multi-parameter forms would not necessarily possess.

3.1 Annealed and Isothermally Annealed 2¼%Cr1%Mo Steel

Subjective examination of inter-laboratory data (1 to 9) shows the strain-controlled fatigue behaviour to be insensitive to cast-to-cast compositional, melt route, product form and heat treatment differences (ie: whether annealed or isothermally annealed). Consequently the continuous cycling information has been treated as a single data file to yield the following best-fit equations for the respective temperature classifications as:

$\Delta\varepsilon_T\ (\%) = 0.587N_f^{-0.068} + 30.536N_f^{-0.454}$ $T \leq 427^\circ C$, 125 data sets

$\Delta\varepsilon_T\ (\%) = 0.498N_f^{-0.066} + 26.076N_f^{-0.463}$ $427^\circ < T \leq 550^\circ C$, 137 data sets

$\Delta\varepsilon_T\ (\%) = 0.518N_f^{-0.078} + 24.993N_f^{-0.476}$ $550^\circ < T \leq 600^\circ C$, 46 data sets

These analyses cover the full cyclic range of the available data (to $\sim 7 \times 10^6$ cycles). The best-fit curves derived from these equations are superimposed on the data points in Figs 1 to 3 (solid lines) and show deviations from the data base at high strain ranges as a consequence of the weighting influence of data included from the high-cycle regime beyond 10^5 cycles. If the analysis is repeated excluding data with $N_f > 10^5$ cycles, then the following equations are obtained:

$\Delta\varepsilon_T\ (\%) = 0.712N_f^{-0.092} + 71.909N_f^{-0.556}$ $T \leq 427^\circ C$, 101 data sets

$\Delta\varepsilon_T\ (\%) = 0.513N_f^{-0.071} + 47.341N_f^{-0.541}$ $427^\circ < T \leq 550^\circ C$, 124 data sets

$\Delta\varepsilon_T\ (\%) = 0.702N_f^{-0.117} + 51.363N_f^{-0.568}$ $550^\circ < T \leq 600^\circ C$, 43 data sets

which bias the curves towards the high strain data points; the sensitivity to data selection is indicated by the plots of these equations in Figs 1 to 3 (broken lines).

Additionally, Figs 1 and 2 contain published curves derived from annealed 2¼%Cr1%Mo steel (17) claimed to be valid over a cyclic range $10^2 \leq N_f \leq 10^8$ where the tests are initiated and stress-stabilised under strain control thereafter cycling to failure under load control at increased frequency. The given equations are:

$\Delta\varepsilon_T\ (\%) = 0.576N_f^{-0.051} + 123N_f^{-0.637}$ $T \leq 427^\circ C$

$\Delta\varepsilon_T\ (\%) = 0.721N_f^{-0.079} + 211.5N_f^{-0.731}$ $T = 538^\circ C$

Although these equations are of similar form to the true Basquin/Coffin-Manson type, their derivation is somewhat different in that the values of the best-fit constants were obtained by a visual graphical method; they are not based on a least squares regression and are not necessarily related to the plastic and elastic strain range vs. life relationships (17). It follows that these derived equations suppress the sensitivity to data selection evident from the present numerical analysis.

Unification of the continuous cycling results is obtained by plotting time to failure vs. cycles to failure where the time to failure data are found to be in approximately inverse monotonic proportion to the strain rate - the majority of the data is available at a continuous cycling strain rate of 4 x 10^{-3}/s, the inverse proportional relationship with strain rate giving a curve displacement 2 orders of magnitude towards longer times to failure when the strain rate is decreased to 4 x 10^{-5}/s as illustrated in Fig 4 for T $\leq$ 427°C data from Refs 1 to 4. The comparative base-lines given on this plot of time to failure vs. cycles to failure are derived from the present best-fit curve analysis at the appropriate temperature range.

The effect of testing temperature manifests itself with respect to the tensile stress (or total stress range) sustained at $N_f/2$ where, in general, the higher the test temperature, the lower the stress range. However, this trend tends to be confused over the temperature range ~ 316°-482°C due to the phenomenon of dynamic strain ageing which occurs under these particular heat treatment conditions. This effect is also shown in the conventional tensile properties of the annealed steels where the 0.2% PS and UTS pass through a maximum at a temperature of ~ 371°C.

3.2 Normalised and Tempered and Quenched and Tempered 2¼%Cr1%Mo Steel

These data are available from Refs 8-13, 15, 16 on forging, plate, pipe and bar products; some of the materials were given additional stress relief heat treatments prior to testing. Generally the data show reduced continuous cycling fatigue properties in terms of total strain range vs. cycles to failure with respect to the best-fit curves for material in the annealed and isothermally annealed conditions, but with the capacity to support higher tensile stress (or stress range) at a given N_f.

Overall, the $\Delta\varepsilon_T$ vs. N_f fatigue data do not appear to be sensitive to cast and product form differences or heat treatment route between N+T, Q+T or either route with additional stress relief heat treatment. This latter point is particularly well illustrated by the Japanese data (11), which apply an extensive heat treatment shown by previous experience to result in significant embrittlement of 2¼%CrMo steel (the so-called GE Step-Cool(18)). The unified data for these heat treatment variants show little difference in terms of time to failure vs. N_f at a given strain rate in common with the $\Delta\varepsilon_T$ vs. N_f data. Again there appears to be a simple inverse monotonic proportionality with strain rate for the time to failure vs. N_f presentations, a decrease in strain rate by one or two orders of magnitude increasing the time to failure by approximately the same factor at a given N_f as illustrated in Fig 5.

The tensile stress at $N_f/2$ for a given N_f decreases with increase in test temperature without concomitant dynamic strain ageing noted for the annealed and isothermally annealed steel classification. This trend is illustrated in Fig 6 for data in (15) where the broken curves represent the predicted behaviour derived from the relevant Basquin analyses elastically converted to stress with realistic values of E-moduli (calculated as 190, 171 and 169 GN/mm^2 at room temperature, 500° and 550°C, respectively).

Inspection of the remaining data shows that the applied additional heat treatments maintain the ambient tensile properties within the relevant ISO requirements (19), consequently these data are considered as a single file for analytical purposes. Further application of the ISO tensile requirements ($275N/mm^2$ min 0.2% PS, $490\text{-}640N/mm^2$ UTS at room temperature) allows discrimination of the high strength levels of the Q+T data noted in Ref 8. Enforcing these restrictions and grouping the data in their respective temperature categories yields analysis as

$$\Delta\varepsilon_T\ (\%) = 0.702N_f^{-0.066} + 52.418N_f^{-0.566} \quad T \leq 427^oC,\ 45\ \text{data sets}$$

$$\Delta\varepsilon_T\ (\%) = 0.524N_f^{-0.055} + 160.751N_f^{-0.779} \quad 427^o < T \leq 550^oC,\ 144\ \text{data sets}$$

$$\Delta\varepsilon_T\ (\%) = 0.343N_f^{-0.029} + 69.497N_f^{-0.664} \quad 550^o < T \leq 600^oC,\ 34\ \text{data sets}$$

Figures 7-9 show the best-fit curves superimposed on the data points together with the best-fit curves relating to annealed 2¼%Cr1%Mo steel in the same temperature categories derived by the same analytical route. In general, the figures show the N+T and Q+T 2¼%Cr1%Mo steel to possess the lower cyclic endurance (displaced by a maximum factor of ∿ 3 from the best-fit lines for the annealed steel) in the low-cycle regime but with the indicated trend that these relativities are reversed for the high cycle region beyond $\sim 10^5$ cycles. Further inspection shows that the curves are well behaved and follow anticipated trends with temperature except for the best-fit curve for N+T and Q+T material at $T \leq 427^oC$ which is seen to converge with the higher temperature curves at lower cycles and must be accepted as an analytical consequence of restricted data.

3.3 2¼%CrMo Variants

A sparse data base is available for 2¼%Cr1%MoV steel in the N+T condition (9); this heat treatment results in a substantially stronger material than plain 2¼%Cr1%Mo steel similarly heat treated as reflected in both the monotonic tensile and tensile stress at $N_f/2$ vs. N_f data. The information presented in (9) for N+T 2¼%Cr1%Mo¼%V and 2¼%Cr1%Mo steels indicates that the continuous cycling high strain fatigue results are comparable for both steels in terms of $\Delta\varepsilon_T$ vs. N_f and time to failure vs. N_f and are, surprisingly, only slightly displaced from the US data base-line for the softer annealed and isothermally annealed material. Analysis of the data yields

$$\Delta\varepsilon_T\ (\%) = 0.398N_f^{-0.006} + 532.583N_f^{-0.91} \quad T = 593^oC,\ 8\ \text{data sets}$$

and the best-fit curve is shown with the data points in Fig 10.

Data covering Q+T Nb-stabilised 2¼%Cr1%Mo steel (14), are also shown in Fig 10 for comparison with the curve generated from the equation given in (20) for the Nb-stabilised variant as:

$$\Delta\varepsilon_T\ (\%) = 0.4N_f^{-0.041} + 78.9N_f^{-0.654} \quad T = 538^oC$$

The figure also contains the superimposed best-fit curve derived from N+T and Q+T plain 2¼%Cr1%Mo steel which is seen to lie close to the best-fit line and revised data points generated for the Nb-stabilised variant (14,20). Thus, although it is recognised that the tenuous data do not allow confident conclusions to be reached, nevertheless the indication is that Q+T Nb-stabilised 2¼%Cr1%Mo steel possesses similar strain-controlled fatigue behaviour to its plain N+T and Q+T steel counterpart and therefore shows the same relativities to the annealed 2¼%Cr1%Mo steel fatigue behaviour as does the plain N+T and Q+T steel category.

4. SUMMARY DISCUSSION

A compilation of the available national and international data on elevated temperature low-cycle strain-controlled fatigue for 2¼%CrMo steel has been made and, where possible, the continuous cycling data have been statistically analysed on the basis of strain range and cycles to failure to yield best-fit equations for defined compositional, heat treatment and test temperature categories given in the text.

The principal indication from the analysis is that the fatigue properties are influenced by the strength level of the material; this in turn is a function of heat treatment route such that annealed or isothermally annealed 2¼%Cr1%Mo steel possesses superior low-cycle fatigue properties by a maximum factor of $\sim$ 3 on cycles to failure in comparison with the higher strength N+T, Q+T and Nb-stabilised versions. Valid data relevant to the Nb-stabilised variant are sparse but it would appear that this information falls in the same population as its plain N+T and Q+T counterpart; the room temperature tensile properties for both these compositional categories satisfy the ISO minimum requirements for the latter classification, but the annealed steel possesses an ambient proof stress below this criterion. The available information, although relatively sparse, suggests that under high-cycle fatigue conditions (beyond $\sim 10^5$ cycles) the higher proof stress steels are likely to exhibit superior endurance to the annealed variant.

Overall, the high strain continuous cycling fatigue data indicate insensitivity to cast-to-cast and product form differences in a particular heat treatment, compositional or test temperature category. Furthermore, the effect of secondary heat treatments simulating fabricational stress relief is not marked in terms of total strain range or time to failure vs. cycles to failure, but manifests itself as a reduction in tensile stress (or stress range) at $N_f/2$ sustainable by the material. Increasing the test temperature results in a progressive decrease in continuous cycling fatigue endurance and sustainable stress range although the latter trend is confused for annealed or isothermally annealed 2¼%Cr1%Mo steel over the temperature range where dynamic strain ageing occurs.

5. CONCLUSIONS

i) For 2¼%Cr1%Mo steels in similarly heat treated conditions and of similar strength level, cast-to-cast and product form variations are insignificant with respect to low-cycle fatigue properties.

ii) The low-cycle fatigue data base for N+T and Q+T 2¼%Cr1%Mo steel superimposes that of the Nb-stabilised variant although it must be recognied that there are only restricted data applicable to the latter steel. Tensile properties for both classifications meet the ISO requirements for N+T and Q+T 2¼%Cr1%Mo steel (275N/mm^{2}min 0.2% PS and 490-640N/mm^2 UTS at room temperature) whereas this minimum proof stress criterion is not met for the annealed variant.

iii) N+T or Q+T 2¼%Cr1%Mo steel possesses poorer low-cycle fatigue properties than annealed or isothermally annealed material (as does the Nb-stabilised variant), displaced by a maximum factor of $\sim$ 3 on cycles to failure from the comparable best-fit lines for the annealed steel.

iv) Available information for N+T and Q+T 2¼%Cr1%Mo and Nb-stabilised steel suggests that under high-cycle fatigue conditions the relativities in fatigue properties with respect to the annealed variant may be reversed ie: higher proof stress material is likely to exhibit the better fatigue properties in excess of $\sim 10^5$ cycles.

v) Test temperature influences the fatigue behaviour in that its increase results in a progressive decrease in continuous cycling fatigue endurance and reduction of the tensile stress at $N_f/2$ that the steel is able to sustain. This latter trend is confused for annealed or isothermally annealed 2¼%Cr1%Mo steel over the temperature range where the dynamic strain ageing phenomenon occurs ($\sim 316^o$-482^oC).

vi) Secondary heat treatments simulating fabricational stress relief appear to have little influence in terms of total strain range or time to failure vs. cycles to failure data within their respective classifications. As expected, the tensile stress (or stress range) at $N_f/2$ sustainable by the material is reduced by additional softening heat treatments.

vii) Where available, presentation of data in terms of time to failure vs. cycles to failure demonstrates an approximate inverse relationship between time to failure and strain rate at a given N_f under continuous cycling conditions. This approximate relationship appears to hold for strain rates in the range $\sim 4 \times 10^{-3}$ to 10^{-5}/s ie: within the data envelope.

6. ACKNOWLEDGEMENT

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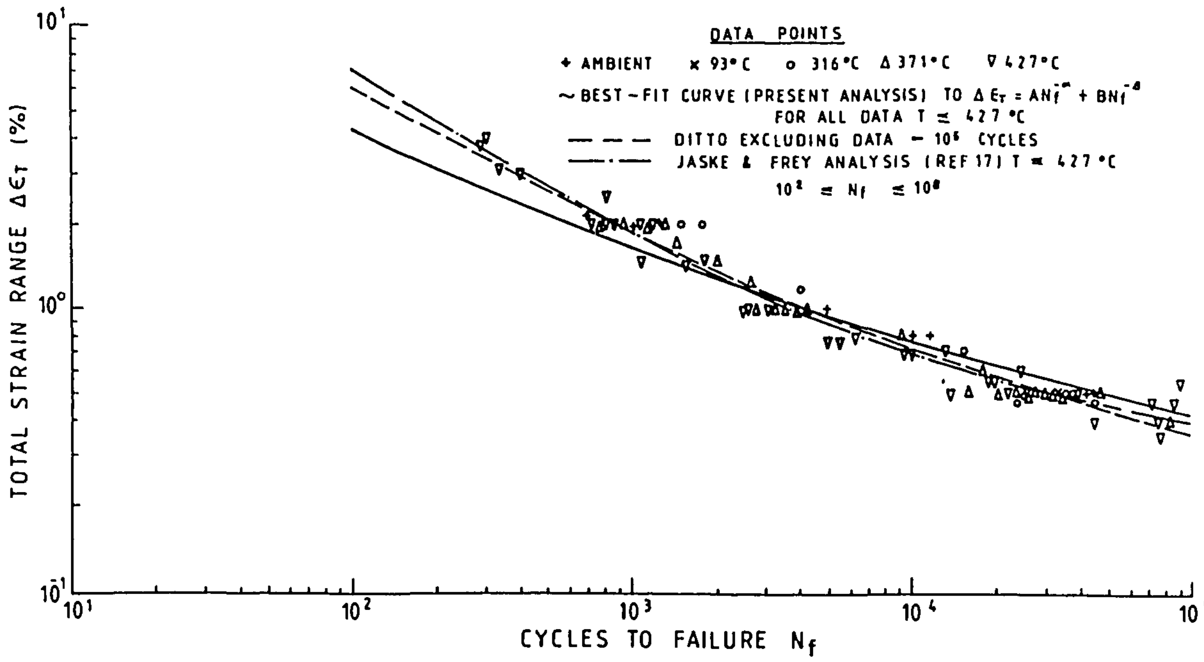

FIG. 1 CONTINUOUS CYCLING STRAIN - CONTROLLED FATIGUE DATA FOR ANNEALED $2\frac{1}{4}$ % Cr 1% Mo STEEL : T ≤ 427°C

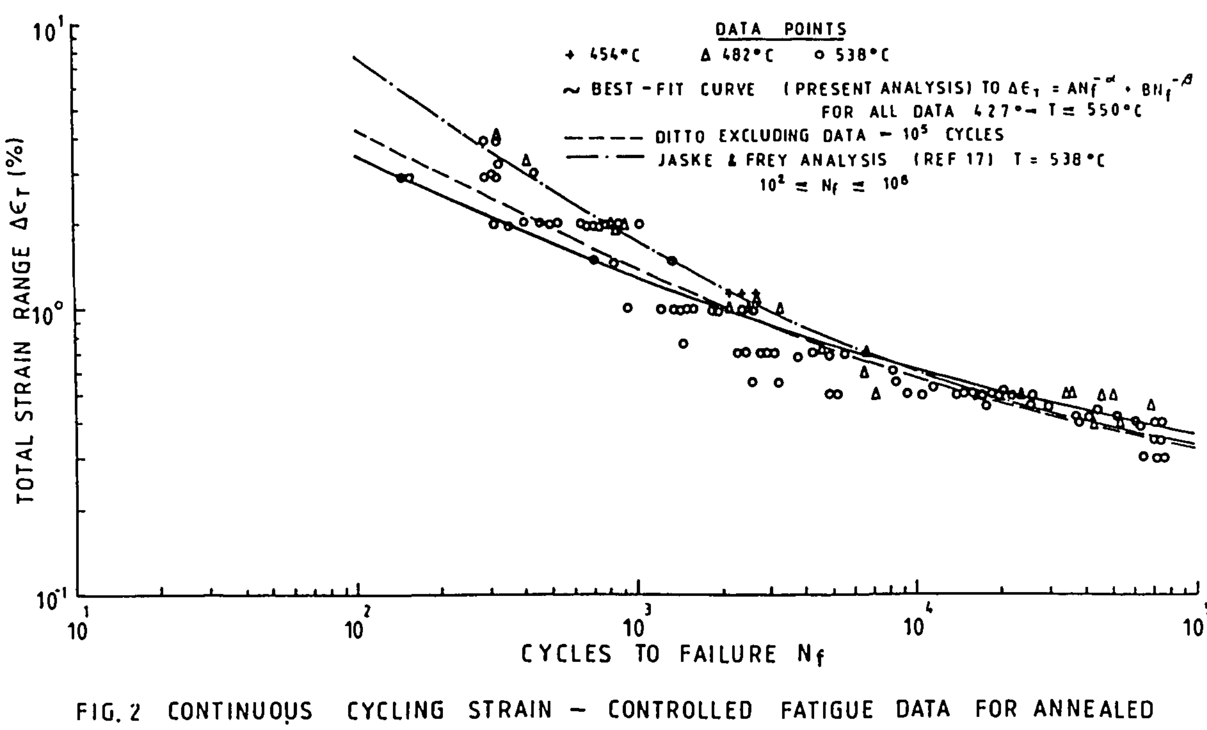

FIG. 2 CONTINUOUS CYCLING STRAIN – CONTROLLED FATIGUE DATA FOR ANNEALED $2\frac{1}{4}$ % Cr 1% Mo STEEL : 427° < T ≤ 550°C

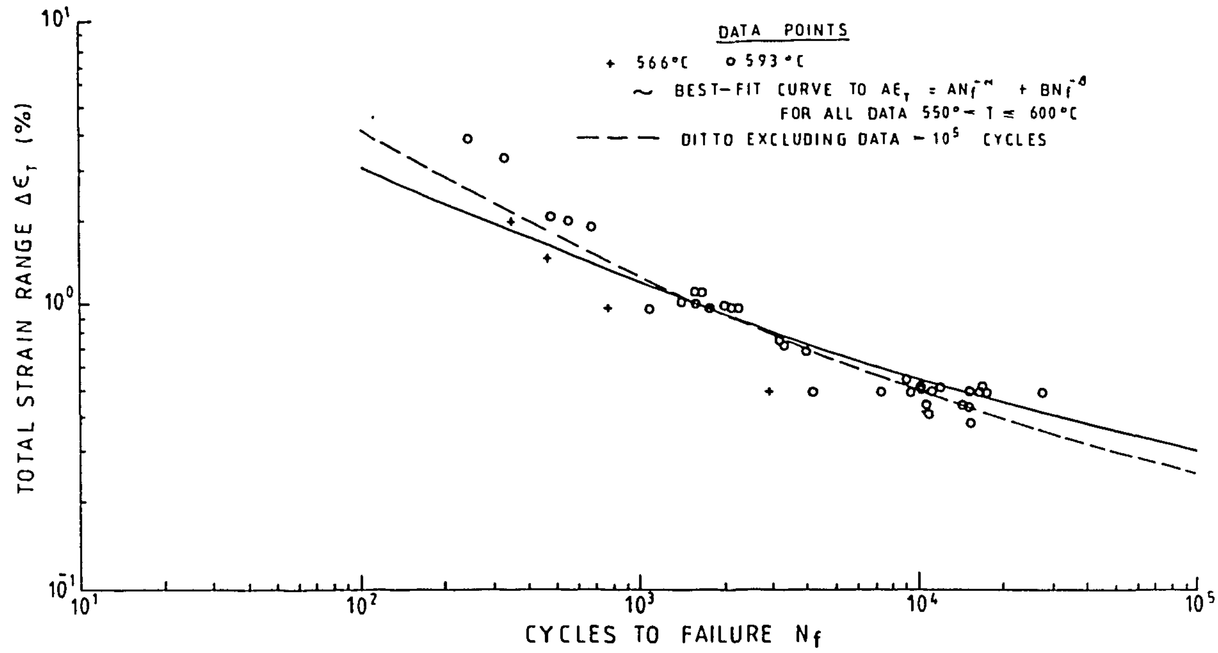

FIG. 3 CONTINUOUS CYCLING STRAIN - CONTROLLED FATIGUE DATA FOR ANNEALED $2\frac{1}{4}$ % Cr 1% Mo STEEL : 550° < T ≤ 600°C

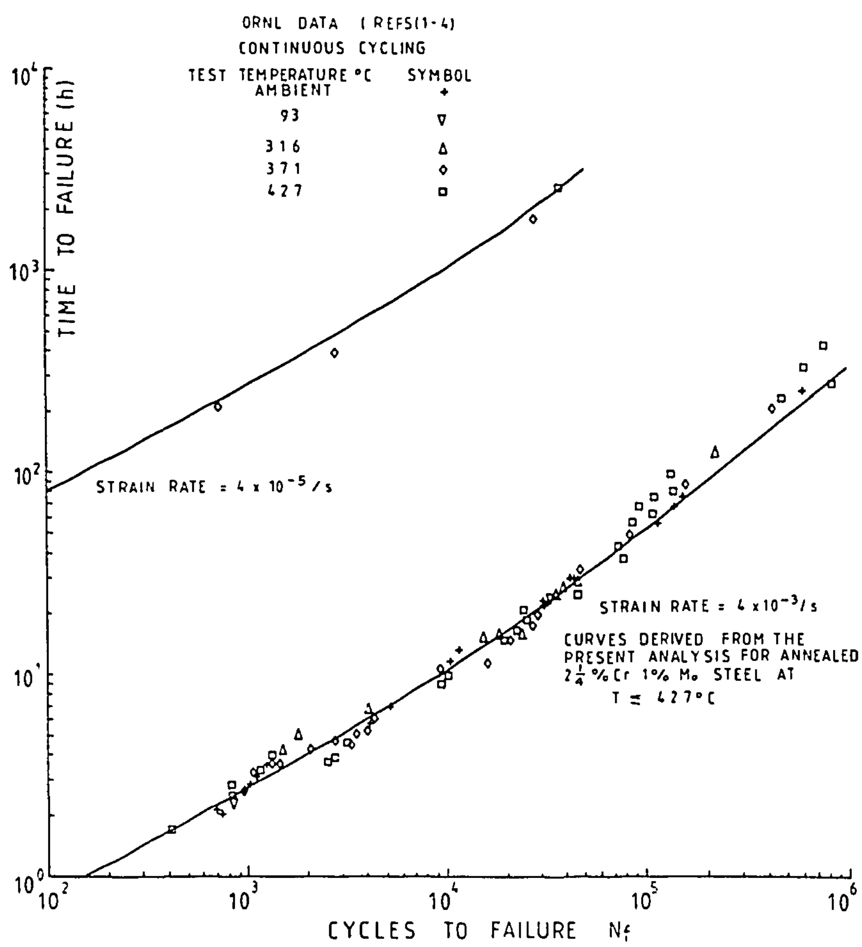

FIG. 4 CONTINUOUS CYCLING STRAIN - CONTROLLED FATIGUE DATA FOR ANNEALED AND ISOTHERMALLY ANNEALED $2\frac{1}{4}$ % Cr 1% Mo STEEL ILLUSTRATING THE APPROXIMATE INVERSE RELATIONSHIP BETWEEN TIME TO FAILURE AND STRAIN RATE

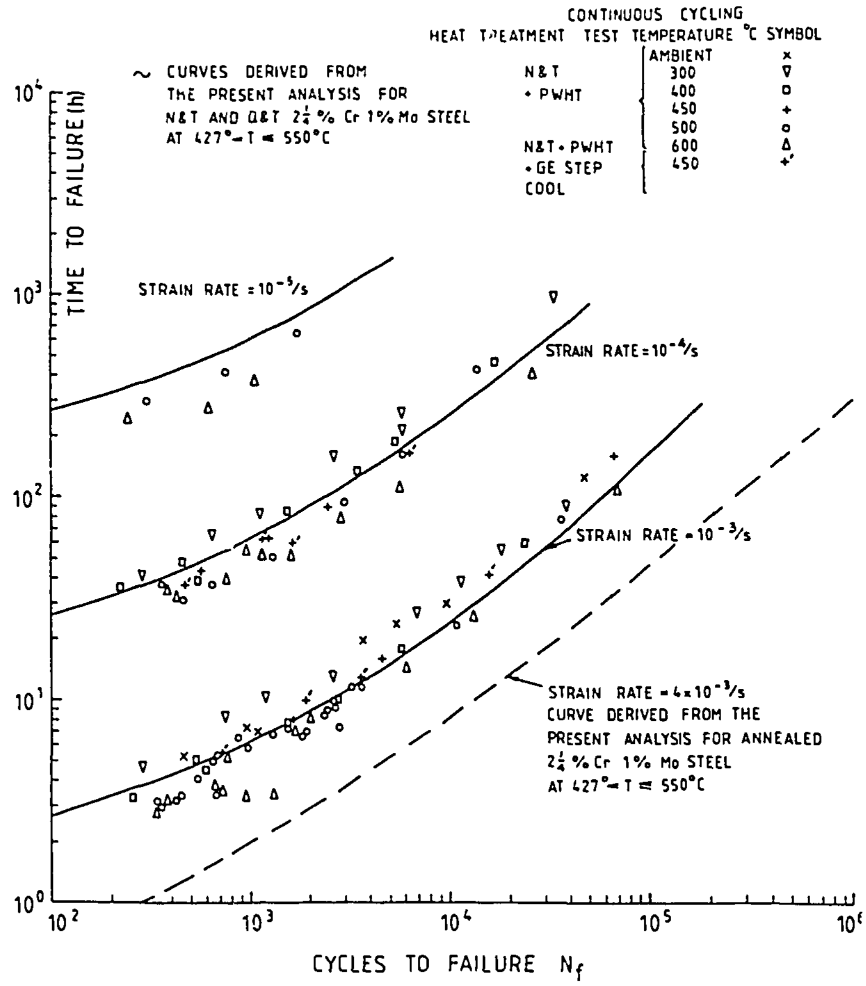

FIG 5 CONTINUOUS CYCLING STRAIN - CONTROLLED FATIGUE DATA FOR N+T AND Q+T $2\frac{1}{4}$% Cr 1% Mo STEEL ILLUSTRATING THE APPROXIMATE INVERSE RELATIONSHIP BETWEEN TIME TO FAILURE AND STRAIN RATE
NRIM & JISI DATA (REFS 11,12)

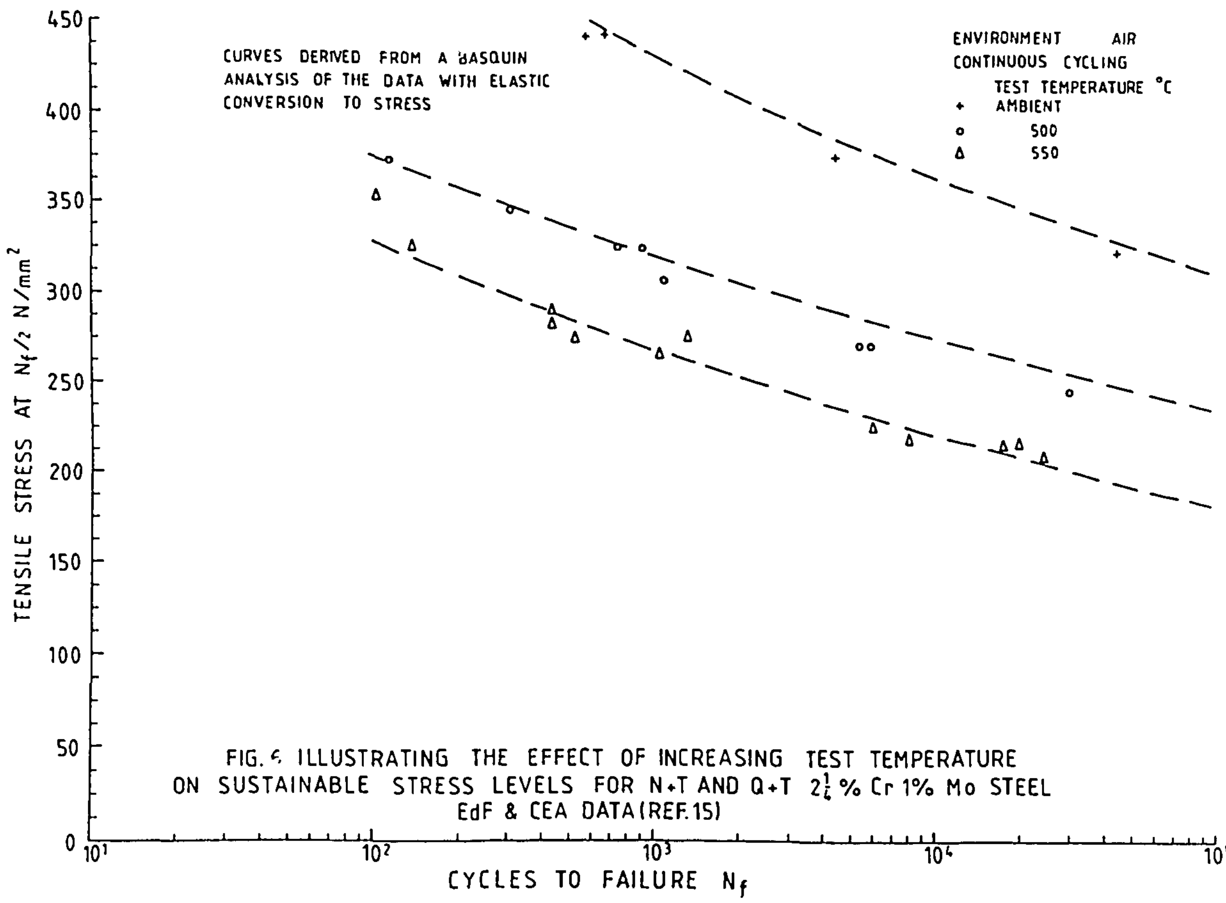

FIG. 6 ILLUSTRATING THE EFFECT OF INCREASING TEST TEMPERATURE ON SUSTAINABLE STRESS LEVELS FOR N+T AND Q+T $2\frac{1}{4}$% Cr 1% Mo STEEL
EdF & CEA DATA (REF. 15)

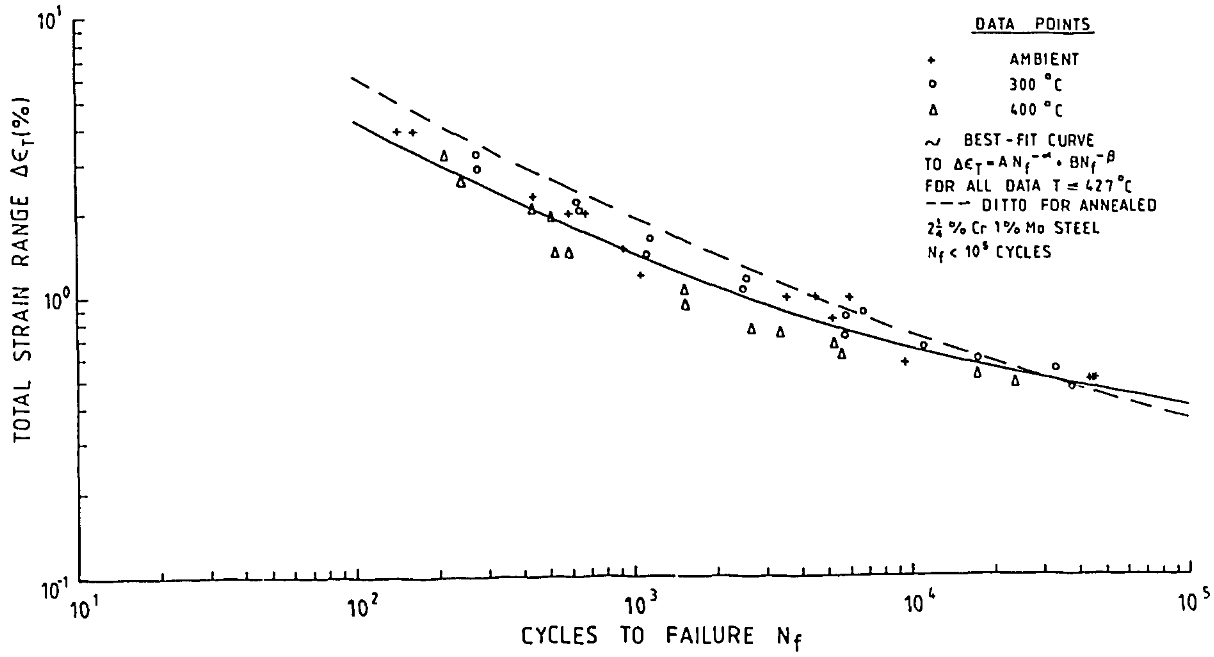

FIG 7 CONTINUOUS CYCLING STRAIN-CONTROLLED FATIGUE DATA FOR N+T AND Q+T 2¼ % Cr 1% Mo STEEL T ≤ 427°C

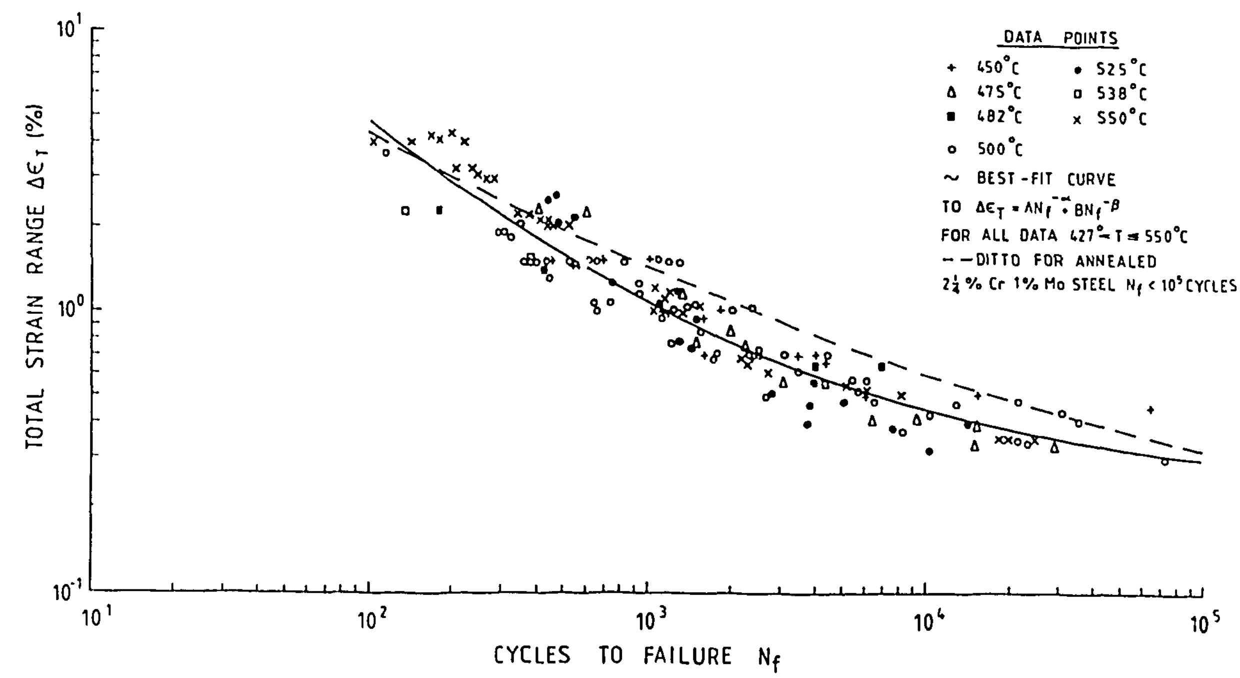

FIG 8 CONTINUOUS CYCLING STRAIN-CONTROLLED FATIGUE DATA FOR N+T AND Q+T 2¼ % Cr 1% Mo STEEL 427 ≤ T ≤ 550°C

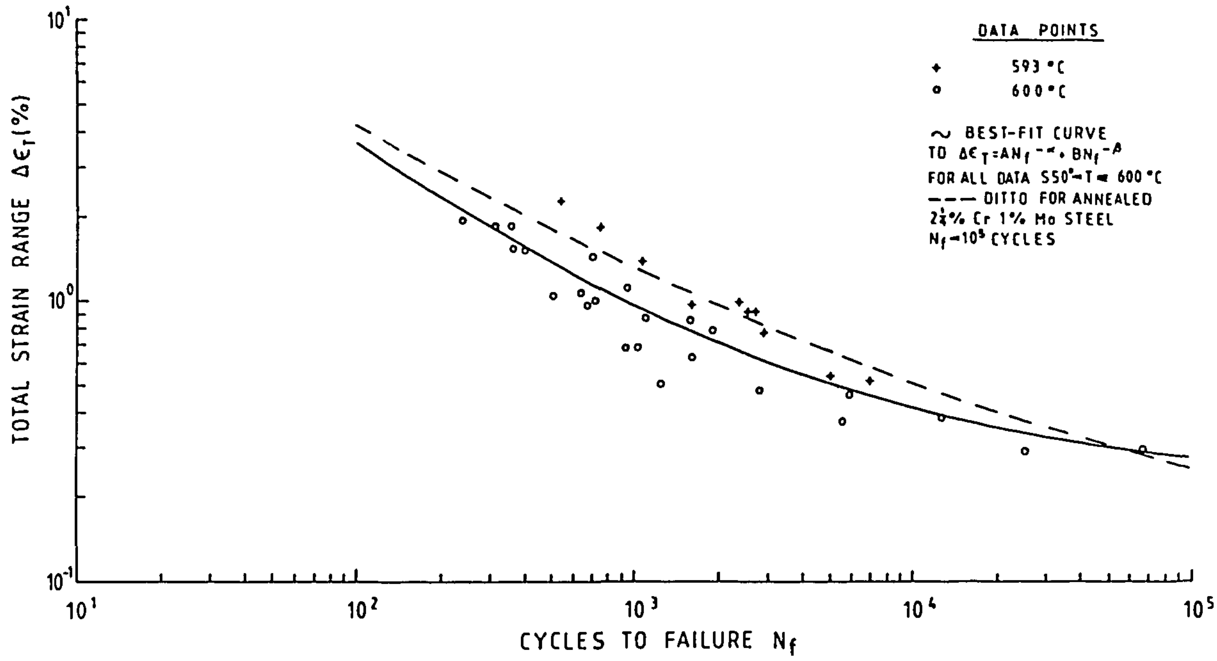

FIG.9 CONTINUOUS CYCLING STRAIN-CONTROLLED FATIGUE DATA FOR N+T AND Q+T $2\frac{1}{4}$% Cr 1% Mo STEEL : 550° < T ≤ 600°C

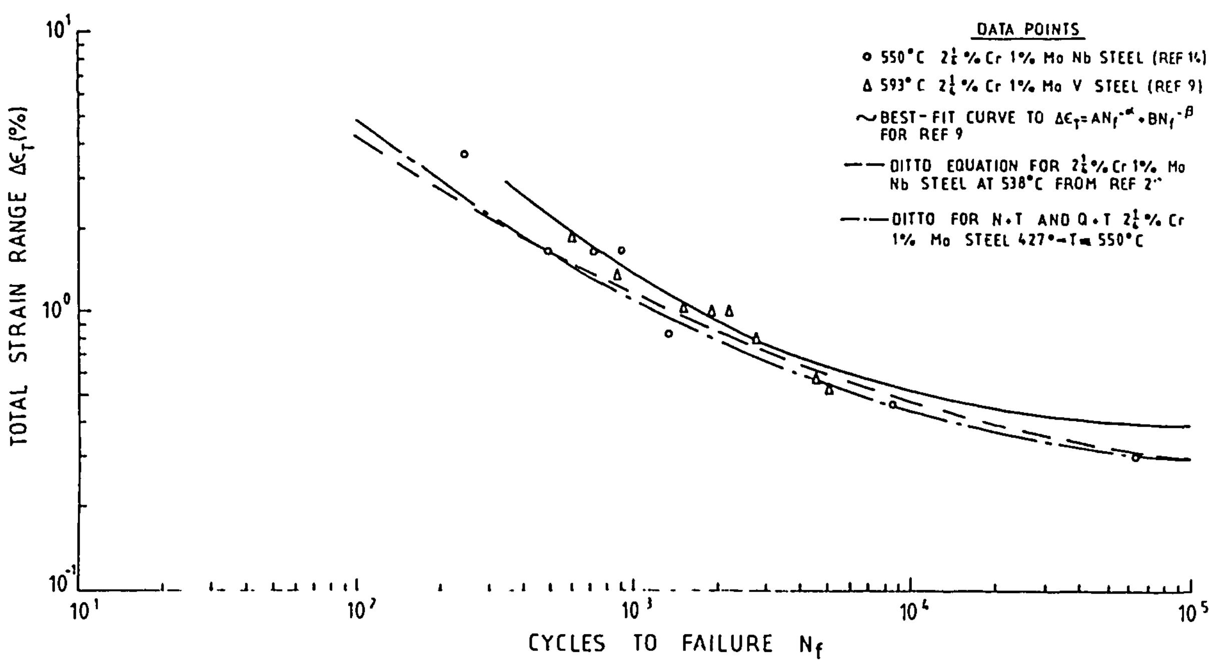

FIG 10 CONTINUOUS CYCLING STRAIN-CONTROLLED FATIGUE DATA FOR N+T AND Q+T Nb OR V CONTAINING $2\frac{1}{4}$ % Cr 1% Mo STEEL