ESTIMATION OF THE CONTROLLING STRESS IN CREEP FRACTURE

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SUMMARY

Identification of the complex-stress criterion governing creep fracture in metals has been a major objective in the high temperature research work at NEL. The implementation of correct criterion in creep design, has been shown to be of fundamental significance in the assessment of component life. The present report considers the problem of the means whereby the criterion may be derived for a particular metal without the availability of sophisticated complex-stress testing equipment and procedures such as the combined tension and torsion tests on thin walled tubular specimens employed in the earlier fundamental researches on the subject.

By investigating a wide spectrum of engineering metals it was established that for homogeneous stress conditions two criteria appeared to be sufficient to cover all the metals studied for complex-stress creep fracture, either the maximum principal stress or the octahedral shear stress criterion. Further, it was found that those metals which developed random and continuous cracking during creep were controlled with respect to fracture time by the maximum principal stress, while metals which showed virtually no cracking were governed by the octahedral shear stress or second order invariant. The physical nature of the final fracture (transcrystalline or inter-crystalline), contrary to considerable current concepts, was found to be unrelated to which criterion was operative.

Having reduced the possible fracture criteria to two, it only remained to develop a simple test method exploiting this finding to achieve the precise identification for a particular metal. Such a test was tentatively explored by one of the authors in a previous study (J. Inst Metals, 1972, 100, 163-171) where solid cylindrical specimens were subjected to direct double shear in a minimally modified conventional tensile creep testing machine.

The maximum difference in equivalent stress representing the maximum principal stress and octahedral shear stress criterion occurs in the biaxial tension-compression quadrant at the position of equal magnitude of principal stress ie pure shear. This fact combined with the power form of the stress dependence of creep fracture time common to metals at elevated temperatures makes the difference in fracture times predicted by the two criteria when applied to pure shear vast indeed. Differences of predicted time are of the order $(\sqrt{3}/1)^{\nu}$ where ν, the creep fracture time stress index, may range from 4 to 7. Thus the readily observable variation of predicted fracture times of the order of 1000 to 5000 per cent may be compared with that realised in the test and identification of the relevant criterion made.

Seven metals including aluminium, copper, titanium, cast iron and three steels have been investigated in the present report at temperatures where creep conditions are operative. The results have shown that the method leads to sufficiently accurate prediction of the complex-stress creep fracture criterion for the metals studied. Supplementary qualitative information on creep curve form and ductility behaviour are a further feature of the method.

1. INTRODUCTION

Failure to identify and implement the appropriate complex-stress, creep fracture time relationship in creep design for components has been shown [1] to lead to considerable error in the prediction of rupture times.

Previous investigations at NEL [2,3] into the relationships between complex-stress and tensile creep fracture data have been mainly directed towards identifying the predominant stress criteria for a significant number of metals rather than developing a simple method whereby this identification might eventually be made without the aid of sophisticated tests.

The fundamental studies involved tests on an accurately known, constant, representative complex-stress system, usually that of combined tension and torsion imposed on thin-walled tubes. By the investigation of a substantial number of different engineering metals and alloys at elevated temperatures, appropriate to the creep regime for the metal concerned, several positive conclusions were arrived at, which it was believed would apply to metals in general. Among those conclusions were that, under homogeneous stress conditions, two criteria dominated the spectrum of possible criteria for complex-stress creep fracture. For metals developing random and continuous cracking (as seen in an optical microscope) during creep, the stress criterion for time to fracture is the Maximum Principal (Tensile) Stress. On the other hand, for metals which show virtually no cracking during creep, the criterion is the Octahedral Shear Stress or Second Order Stress Invariant. No relationship was detected between the physical nature of the final fracture (ie transcrystalline or intercrystalline) and the criterion appropriate to the metal considered.

Accepting that two criteria for complex-stress creep fracture applied to all metals, the designer aided only by tensile creep tests would require to identify which of the two applied to the particular metal and temperature with which he was concerned.

Although previous work [2] had suggested that the identification of the criterion could generally be made on the basis of the creep-cracking characteristics of the metal as revealed by fractured tensile creep specimens, under certain circumstances, ambiguity could arise in deciding into which cracking category a metal fell when cracks were evident but few in number.

A creep fracture test capable of being used to identify the criterion, yet as simple as the tensile test, was required. This information would supplement the indications afforded by the cracking characteristics of fractured tensile creep specimens.

A test which would fulfil the need was tentatively explored by one of the authors in a previous paper [4], and in the present paper is shown to provide a solution to the problem for a wide range of metals and temperatures. The success of the tests appear to justify the expectation that the method might aid identification of the appropriate complex-stress creep fracture criterion for metals in general. The creep fracture test advocated is a direct shear test, using inexpensive solid cylindrical specimens and a very simply modified conventional tensile creep unit (Fig 1), in conjunction with normal tensile creep fracture data.

2. THEORY

The method of identification of the stress criterion from the evidence of direct shear creep fracture test data rested on:

(a) acceptance that either the Maximum Principal Tensile Stress or the Octahedral Shear Stress was the dominating, if not the precise criterion [5] for a given metal under complex-stress creep conditions, and

(b) the major difference in fracture times predicted by the two criteria when applied to forecasting the fracture time of a pure shear test from the equivalent pure tensile test (or tensile creep fracture stress/time equation). It was postulated that the vastly different fracture times predicted and subsequently compared with those in direct shear creep tests, would clearly indicate the correct criterion.

The reasons for the large difference in fracture times predicted by the two criteria is that firstly, for pure shear conditions, the representative stresses respectively indicated by the two criteria show the greatest numerical difference for all possible combinations of biaxial stress. The effect of this stress difference is, however, additionally magnified when related to time because of the high stress dependence of creep fracture times (Fig 2) or the curvature of the stress/fracture time curves. This stress dependence is frequently about 5 or 6, and can often be as high as 7 or 8. Since the tensile stress equivalents for pure shear on the basis of Octahedral Shear Stress or Maximum Principal Tensile Stress are in the ratio $\sqrt{3}/1$, fracture times predicted by the two criteria from tensile creep data are in the ratio $(\sqrt{3}/1)^{\nu}$ where the stress dependence of fracture time t_f is given by the equation

$t_f = A\,\sigma^{-\nu}$, where A and ν are constants for a given metal and temperature. (See Appendix)

Thus fracture time predictions of pure shear tests from tensile creep fracture* data would be in the ratio 26.8/1 for a stress index of 6, and 46.4/1 for $\nu = 7$.

The differences in predicted times of creep fracture thus provide a convincing supplement to the methods advocated in past work, which related creep fracture cracking characteristics to the complex-stress creep fracture criterion.

3. MATERIAL AND TEST MACHINES

The metals tested were an aluminium alloy, a commercially pure copper, a 0.24%C steel, a cast iron, a titanium alloy, a ½%Cr½%Mo¼%V steel and Nimonic 90. All the metals were studied at a temperature within the working range of the metal concerned and at which creep conditions prevailed. Details of the metals and heat treatments are given in Table I.

The tensile creep tests were made using solid cylindrical specimens in conventional double-lever Denison 5ton capacity creep machines.

The direct double-shear creep fracture tests were made in similar tensile creep machines modified only by the addition of an adaptor assembly, Fig 1, which converted the direct tensile stressing system to one of double-shear imposed on solid cylindrical specimens (12.7 or 9.07mm diameter and 38.1mm long). Thermocouples were attached to the two outer ends and a third thermocouple was fixed to the adaptor tongue opposite the mid-section of the specimen. Temperature control of 1.5°K and a gradient of 2°K was obtained.

The combined tension and torsion creep fracture tests on thin-walled tubular specimens were made in the machines designed and described previously by Tapsell and Johnson [6].

4. TEST RESULTS

Table II lists the direct shear tests performed on the different metals, and the test temperatures. Nominal shear stresses are given in MN/m^2 and represent the initial condition after the application of the final loading increment. Actual fracture times of the tests are

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* Although neither linearity nor log/log relationships for stress and fracture time may by invariable, this is inconsequential; the equivalent stress may still be obtained directly from the data.

next shown alongside the times of fracture predicted using the two possible creep fracture criteria, and either a tensile creep fracture equation or the results of tensile creep fracture tests at the corresponding stress levels according to the two stress criteria. Finally, the stress criterion indicated by the present method is compared with that indicated by the creep-cracking characteristics of fractured tensile creep specimens and confirmed by previous work using torsion or combined stress tests.

5. DISCUSSION

Table II reveals that for the aluminium, copper, 0.24%C steel and titanium alloy, the complex-stress creep fracture criteria were clearly identified by the direct shear creep fracture tests and confirm the indications afforded by the creep-cracking characteristics of the metal.

The Flake Graphite Cast Iron had not been studied in the earlier work on complex-stress creep fracture using combined tension and torsion tests on thin walled tubes. However, as part of the programme on solid cylindrical bars reported in reference 1, the torsional tests' fracture surfaces eg (Fig 3) convincingly displayed compatibility with failure along the surface under maximum principal tensile stress. The direct double shear creep fracture test results in Table II confirmed this indication of criterion.

The $\frac{1}{2}$%Cr$\frac{1}{2}$%Mo $\frac{1}{4}$%V steel at 575°C is the material most recently studied, and the present results are part of a comprehensive test programme on it. Again an octahedral criterion is indicated by the shear tests and confirms the failure surface characteristics of solid torsional testpieces which were identical to that shown by the titanium alloy (Fig 3).

Only in Nimonic 90 has any difference been observed between the criterion indicated by the shear tests and that in previous complex-stress studies. Johnson and Khan identified the creep fracture criterion for this metal at 750°C [3] as the maximum principal stress, and found this compatible with the crack-forming behaviour of the metal under creep conditions. In contrast, the results in Table II suggest that the correct criterion for the metal is the octahedral shear stress. Detailed study of the creep fracture characteristics of the forged cube form of this metal, as used by Johnson and Khan, has revealed a significant specimen size effect for creep fracture. Fracture times for the same tensile stress of 170 MN/m^2 at 750°C on 0.51mm wall thick tubular specimens, as used in the previous work, and 6.35mm and 9.07mm diameter solid specimens gave fracture times of 337, 412 and 2560 hours respectively, while again the same comparison using Johnson's test on a thin-walled tube at a tensile stress of 146.7 MN/m^2 (9.5tonf/in^2) and a tensile creep test on a 9.07mm diameter conventional specimen gave fracture times of 242 and 5591 hours respectively. It is evident that the necessity, due to load limitations, to use 0.51mm wall thick specimens and thus only 2 to 3 grains across the wall, combined with the significant size effect would have affected the tube results. A further complication in the study of Nimonic 90 was the low creep fracture ductility and high degree of notch sensitivity. This aspect, among the other factors highlighted by the tests on this metal, is currently being considered.

For Nimonic 90 at 750°C the evidence on the complex-stress creep fracture criterion is thus conflicting, Johnson's data and the crack-forming characteristics suggesting a maximum principal stress criterion, while that afforded by the direct shear tests indicates an octahedral criterion. This leads to the question of criterion to be used in the absence of confirmed or positive indications of which is appropriate. Against the background of metals in general, it appears that the octahedral criterion is the most common of the two criteria considered; it is more-conservative for design purposes and should obviously be used when in doubt. This attitude seems appropriate when considering Nimonic 90 at 750°C.

The restriction of the fracture surface to one plane in the shear tests as distinct from the freedom of the tensile or torsional counterparts to fail at the weakest plane, is an impediment to using the failure times as basic data. Further, the true stress distribution during creep, though likely to tend to the average by redistribution, may nonetheless be complex, particularly for those metals with low creep ductility or high notch sensitivity. Anisotropy may also be significant. However, in general, the large difference between the times (up to two orders of magnitude) predicted by the two criteria, will far outweigh those impediments to identifying the correct criterion.

The direct double-shear creep fracture tests may additionally provide qualitative comparisons of creep deformation curves from readings of a dial gauge contacting the lower adaptor of the creep unit. Typical comparisons of such test curves with the corresponding tensile or pure torsional test results are shown in Figs 4 and 5. Finally, direct estimates of the creep behaviour of components such as shear studs, gudgeon pins, and fir-tree root fixings of turbine blades are obtainable from the tests or from the tensile creep fracture data combined with the stress criterion.

It now seems clear that for the majority of steels, and perhaps most metals, the stress system controlling creep fracture is the octahedral shear stress. The present method will, however, help to identify those metals which follow the alternative maximum principal stress criterion.

Ultimately, the designer must resolve whether the advantages to be derived in the simplification for design of accepting a single criterion, the octahedral shear stress, outweighs the disadvantages of occasional overdesign when the metal is, in fact, controlled for creep fracture by the maximum principal tensile stress. The component conditions and environment and the penalties incurred through over-design will decide the issue.

ACKNOWLEDGEMENTS

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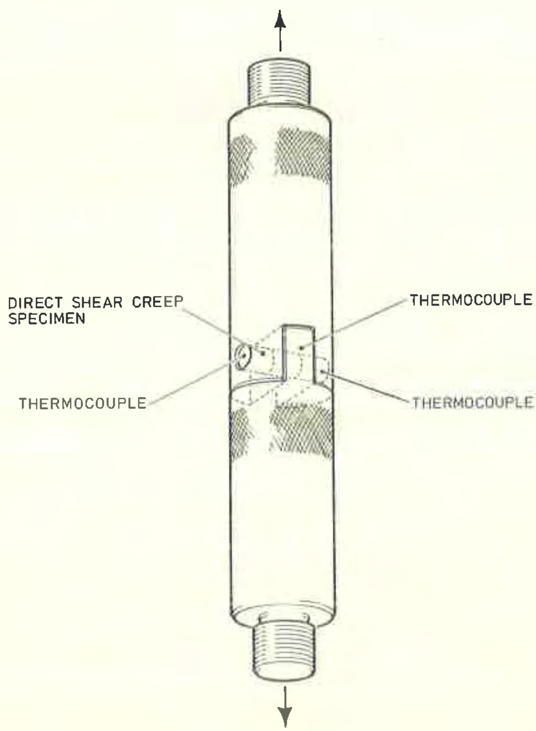

Fig. 1 Modified Adaptor for Direct Double Shear Creep Fracture Tests

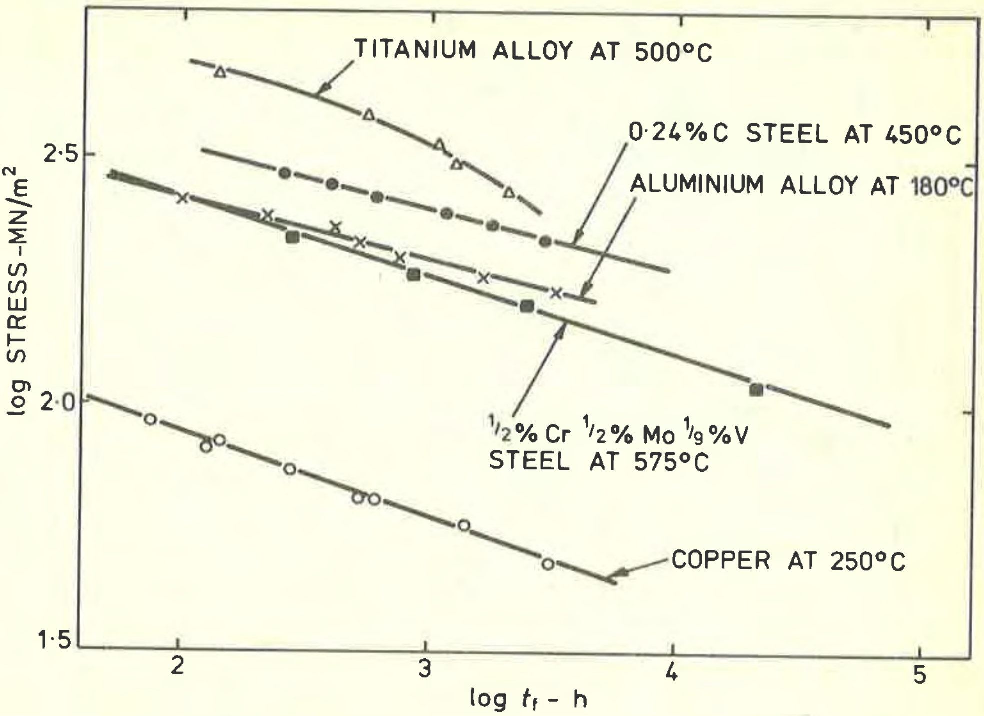

Fig. 2 Basic Stress-Creep Fracture Time Data

Fig. 3 Fractured Torsion Specimens

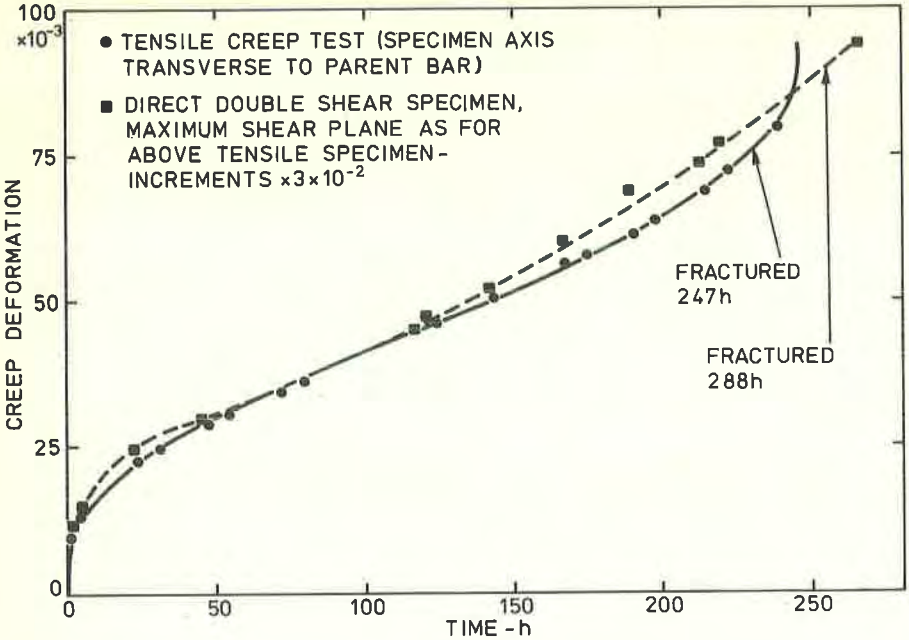

Fig. 4 Aluminium Alloy RR58 at 180°C. Shear Stress = 121·5 MN/m^2

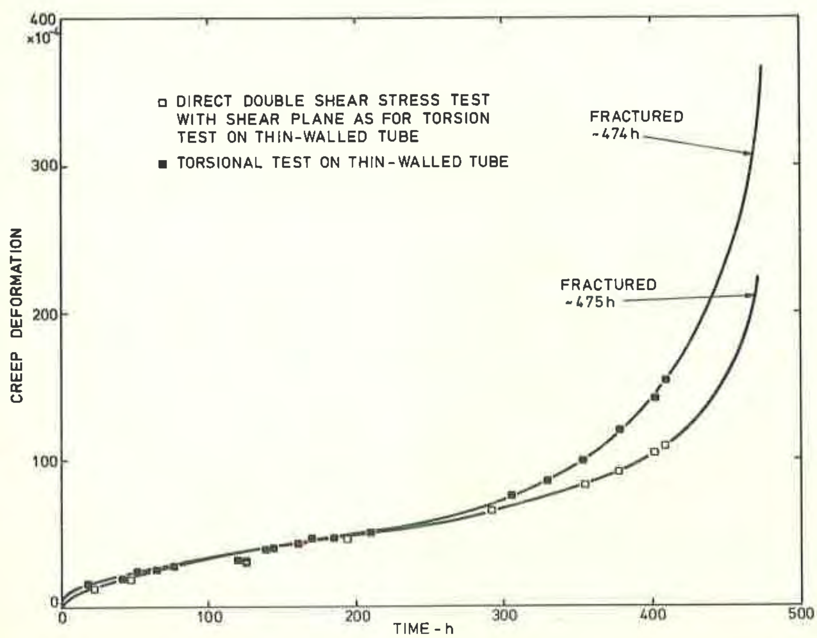

Fig. 5 Commercially Pure Copper at 250°C Shear Stress = 65·4 MN/m^2

APPENDIX

THE RATIO OF FRACTURE TIME PREDICTIONS

The octahedral shear stress τ_o is given by

$$\tau_o = \frac{1}{3}\sqrt{\{\Sigma(\sigma_1 - \sigma_2)^2\}}$$

where σ_1, σ_2, σ_3 are principal stresses.

Thus for pure tension σ,

$$\tau_o = \frac{\sqrt{2}}{3}\sigma$$

and the representative tensile stress σ_o^* according to the octahedral shear stress criterion is for the general case,

$$\sigma_o^* = \frac{1}{\sqrt{2}}\sqrt{\{\Sigma(\sigma_1 - \sigma_2)^2\}}.$$

Similarly, according to the maximum principal stress criterion the representative tensile stress σ_1^* is

$$\sigma_1^* = \sigma_1 \quad (\text{for } \sigma_1 > \sigma_2 > \sigma_3).$$

For pure shear or pure torsional stress S,

$$\sigma_1 = S, \quad \sigma_2 = 0, \quad \sigma_3 = -S.$$

Thus

$$\sigma_o^* = \sqrt{3}\,S \quad \text{and}$$

$$\sigma_1^* = S.$$

For a tensile stress-creep fracture time relationship of the form

$$t_f = A\sigma^{-\nu}$$

where t_f = creep fracture time,

σ = stress, and

A, ν = constants for a given metal and temperature.

The ratio of creep fracture times predicted by the two criteria for the case of pure shear is given by

$$\frac{t_f(\tau_o)}{t_f(\sigma_1)} = \frac{A(\sigma_o^*)^{-\nu}}{A(\sigma_1^*)^{-\nu}} = \frac{A(\sqrt{3}\,S)^{-\nu}}{A(S)^{-\nu}} = \left(\frac{\sqrt{3}}{1}\right)^{-\nu}.$$

TABLE I

DETAILS OF PRODUCTION, HEAT TREATMENT AND CHEMICAL COMPOSITION OF METALS TESTED

Metal	Production and dimensions	Heat treatment	Chemical composition (%)
Aluminium Alloy RR58	Slab 915 x 851 x 76 mm; stretched 2¼ per cent, 5h 20 min after quenching	530 ± 5°C and quenched in water not exceeding 40°C; aged for 30h at 190°C	Cu Fe Si Mn Mg 2.60 1.05 0.07 0.06 1.50 Ni Zn 1.18 0.04
0.24%C Steel	Core from ingot; 406.4 mm dia. and 876.3 mm in length	3h at 950°C followed by air cooling, then 15 min at 930°C followed by air cooling and finally a stress relieving treatment of 3h at 575°C with furnace cooling	C Si S P 0.24 0.32 0.036 0.033 Ni Cr Mo Cu 0.27 0.09 0.03 0.16 Sn Mn 0.005 0.69
Copper	Rolled bar; 38.1 mm dia.	400°C for 1h and furnace cooled	Commercially Pure
Flake Graphite Cast Iron	Cast bar; 101.6 mm dia. and 508 mm in length		TC Si Mn S P 3.26 1.73 0.65 0.097 0.25
Titanium Alloy (Hylite 50)	152.4 mm cube equally forged in three directions	Standard solution* treated and aged	Al Mo Sn Si 3-5 3-5 1.25-2.5 0.3-0.7
Nickel Cobalt Chromium Alloy Nimonic 90	152.4 mm cube equally forged in three directions	Standard solution* treated and aged	C Cr Co Ti Al 0.11 21.1 18.7 2.5 1.5 Fe Si Mn Ni 1.5 0.65 0.5 Rem
½%Cr½%Mo ¼%V Steel	Forged pipe; 355 mm o.d. x 233 mm nominal bore	Noramlised at 970°C for* 2½h, cooled in still air. Tempered at 700°C for 5h, cooled in still air	C Si Mn S 0.12 0.30 0.43 0.024 P Cr Ni Mo V 0.014 0.36 0.21 0.57 0.23

* Heat treated by Manufacturer

TABLE II

Metal	Temp. °C	So MN/m^2	t_f h	Calculated t_f by τ_0 criterion h	Calculated t_f by σ_1 criterion h	Criterion according to So	Criterion according to cracks	Criterion according to CS tests
Aluminium Alloy RR58	180	108.9 121.5 121.5 121.5 163.2	936 288 312 479 63	1 016 479 479 479 30	44 000 20 600 20 600 20 600 2 754	τ_0	τ_0	τ_0 (Ref 7)
Commercially Pure Copper	250	50.0 59.0 65.4 76.7	2 208 672 231 50	77 30 17 7	1 726 679 374 150	σ_1	σ_1	σ_1 (Ref 2)
0.24%C Steel	450	169.5 190.0 200.0	700 259 54	511 160 90	29 790 14 930 10 789	τ_0	τ_0	τ_0 (Ref 2)
Flake Graphite Cast Iron	350	178.0 201.0 251.7	20 000+ 870+ 0	0 0 0	6 927 $<$ 357 0	σ_1	σ_1	σ_1 (Ref 1) and Fig 3
Titanium Alloy	500	201.0 227.0 267.0	2 088 1 054 408	957 679 342	6 896 4 443 2 472	τ_0	τ_0	τ_0 Fig 3
Nimonic 90	750	93.0 124.0 170.0	4 000+ 866 236	1 766 481 114	21 152 5 762 1 366	τ_0	τ_0/σ_1	σ_1 (Ref 3)
$\frac{1}{2}$%Cr$\frac{1}{2}$%Mo$\frac{1}{4}$%V	575	100.0 131.0 162.0	2 900 554 142	1 230 228 60	38 987 7 212 1 909	τ_0	τ_0	

+ Continuing

CS - Complex Stress