LOW CYCLE FATIGUE BEHAVIOUR OF 1% CrMoV STEEL USING A NEW MULTIAXIAL TEST FACILITY

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A highly-versatile microcomputer-controlled fatigue test facility is described, which can simulate any complex stress or strain state, eg every conceivable biaxial stress state represented by principal stress ratios between equibiaxial and pure shear, together with any desired maximum principal stress orientation.

High strain fatigue tests have been performed on 1%CrMoV steel, for a range of multiaxial stresses covering both case A and case B strain states. Cyclic deformation data are presented on a basis of von-Mises and Tresca criteria. Two equivalent strain criteria, are assessed with respect to endurance results.

INTRODUCTION

In engineering components that are of intricate shape and/or simultaneously subjected to several different modes of loading, the state of stress at the critical area is often multiaxial. When designing such components for a low number of cyclic load applications, localized yielding can be permitted to a limited extent and the design is governed mainly by the high strain fatigue properties of the material. Thus, knowledge of cyclic behaviour is important for an accurate assessment of the structural integrity of such components.

The surface multiaxial stress states associated with engineering components may range from pure shear, $\lambda = -1$ to equibiaxial, $\lambda = 1$, where λ is the ratio of the surface principal stresses. The stresses may vary in a non-proportional manner so that both the value of λ, and the magnitude and orientation of the maximum principal stress at the critical location, may continuously change with time in a complex manner. More importantly, different crack systems, case A and case B (1), may dominate and fatigue endurance can be significantly influenced, depending on the orientation and the severity of the stress state coupled with anisotropic material behaviour.

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However, the majority of high strain fatigue and cyclic deformation studies are performed using simple loadings, eg axial, bending, torsion or axial plus torsion, which can only generate limited stress ratios and limited loading patterns, hence the results cannot provide sufficient material information for designing many components. As none of the above mentioned methods enable an independent control of the orientation of the maximum principal stress, nor the generation of a range of stress ratios that cover both case A and case B strain states, these methods have severe limitations when studying anisotropic materials and the creation of dominant crack systems which influence endurance. Without an investigation of these effects, it is impossible to assess the accuracy of available criteria or to develop, with a high degree of confidence, new criteria for the complete range of biaxial stress states.

In this paper a new test facility is described which is able to provide a complete range of biaxial stress states and which can study both isotropic and anisotropic materials. The cyclic deformation and high strain endurance data for a low alloy steel are used to assess widely-used deformation and multiaxial fatigue criteria.

FATIGUE TESTING FACILITY

The testing facility (2), schematically shown in Fig 1, is able to strain a tubular specimen using four loading systems; ie axial load, torque, internal pressure, and external pressure. The loads are independently servo-controlled and can be applied in any desired combination, in- or out-of-phase. Every biaxial stress state, being those represented between equibiaxial and pure shear, can be chosen, together with any maximum principal stress orientation (3).

The machine main frame is a Schenck Hydropuls tension-torsion system, housed in a four-column vertical structure. The combined actuator system is mounted underneath the machine base and is capable of exerting axial load and torque up to +/- 400 kN and +/- 1000 Nm, respectively. The internal and external pressures are created using two hydraulic intensifier systems, both being capable of controlling pressures in the range 0-1700 bar. The specimen is mounted between two chucks connected to the actuator and the upper crosshead via two loading rods. The combined load cell is mounted on the lower rod. Internal pressure is via the upper rod which is sealed on the specimen bore using a closely machined mandrel. A purpose built pressure vessel, mounted on a secondary crosshead, encloses the specimen during external pressurising tests. The pressure vessel is moved vertically away when changing specimens. The dynamic high pressure seals between the rods and the vessel are designed specially to avoid excessive friction and oil leakage. To eliminate the friction influence on load measurements, the load cell is placed inside the vessel. An automatic high pressure oil make-up system is provided so that tests can be conducted uninterrupted, even with a small amount of leakage.

A specially built multiaxial extensometer, used for strain measurement, is mounted on the specimen at a fixed gauge length by means of six radial pins. The strain signals are deduced by using variable inductance transducers whose form and arrangement on the extensometer have been designed to eliminate hydrostatic pressure, bending and misalignment effects on the strain signals. The four actuators are feed-back servo-controlled, using separate Schenk Hydropuls control channels. All three loading modes, axial, torsional and circumferential can be either strain or load controlled. A microcomputer (4) connected via interface hardware enables the generation of command signal waveforms plus acquisition of sampled data for 15 different signals. Special routines permit comprehensive data processing.

MATERIAL, SPECIMEN, TEST PROGRAMME AND RESULTS

The test material is a 1%CrMoV steel with properties given in Ref (5). The specimens were machined from cold rolled bars and used without any heat treatment or stress relieving process. They consist of a 16mm diameter bore, 20mm outside diameter with a 20mm parallel gauge section. The bore is fine honed and the outside surface hand-polished to an 880 grit finish.

Strain controlled, constant amplitude tests were performed with nine different strain states, namely uniaxial, torsion, in-phase combined axial+torsion (A+T) tests with α values of 1.0, 1.5, 2.0, plus four in-phase combined axial+pressure (A+P) tests with β values of -0.7, -0.4, 0 and 1.0. Here

$$\alpha = \Delta\gamma/\Delta\varepsilon(z) \quad \text{and} \quad \beta = \Delta\varepsilon(\Theta)/\Delta\varepsilon(z)$$

where $\Delta\gamma$, $\Delta\varepsilon(z)$, and $\Delta\varepsilon(\Theta)$ are the torsional, axial and hoop strain ranges respectively. All tests were fully reversed with zero mean strain using sinusoidal waveforms with a maximum strain rate in the range 0.002 to 0.004/sec. Tests were stopped at a 5% rapid decay of load range below the quasi-stable value. Pressure tests were terminated when internal pressure control became difficult due to oil leakage from the presence of a crack.

The 1%CrMoV steel showed considerable cyclic softening behaviour for all loading conditions. An initial rapid softening was observed, of about 5 to 10% load range, within 5 to 10% of life. In many tests softening continued to failure, although with a much reduced gradual softening rate.

The cyclic stress-strain curve, based on half-life data, is shown in Fig 2a in terms of the Tresca criterion and in Fig 2b with the von-Mises criterion. The fatigue endurance results are presented in terms of maximum shear and octahedral shear equivalent strains in Figs 3a and 3b respectively.

DISCUSSION AND CONCLUSIONS

Due to the scatter in Fig 2, it is not possible to favour either the Tresca or the von-Mises criteria when correlating cyclic deformation data. When comparing results for multiple step tests for uniaxial and torsional stress-strain behaviour (2), the later criterion was found to be slightly better. Lower stress amplitudes are obtained for axial-pressure tests compared to axial-torsion tests, which may be due to the approximate (ideal plastic) stress analysis used. Exact stress analyses which take account of the stress gradient in the specimen may be required for more accurate results.

As seen in Fig 3, both maximum and octahedral shear equivalent strain criteria are unable to correlate fatigue endurance for all the strain states tested. Case A strain states, which lead to dominant surface cracks, give a longer life compared with the uniaxial state. Case B states however provide more dangerous deep cracks that result in lower lives. Similar lives were observed for Case A strain states under both axial-pressure and axial-torsion loads (compare $\alpha = 2$ with $\beta = -0.7$) which indicates a minimal influence of loading mode on fatigue life. It is also seen that the maximum shear criterion is more suitable for case B strain states than the octahedral shear criterion.

Results clearly indicate the inadequacy of these two single-parameter equivalent strain criteria. A more flexible two-parameter criteria is required (1, 6) for correlating data for all strain states. However a thorough investigation of such criteria is not possible without a test facility as described above. Such a facility also enables study of the damaging influence of different loading parameters under different complex straining conditions. For example the ability to vary the orientation of strain state independent of other damage parameters is ideal for testing anisotropic materials.

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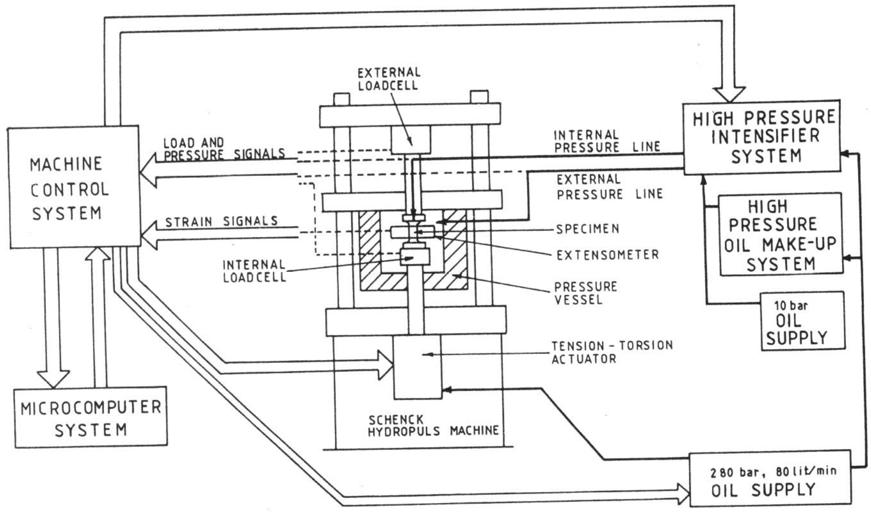


Fig. 1. Schematic layout of the Multiaxial Fatigue Testing Facility

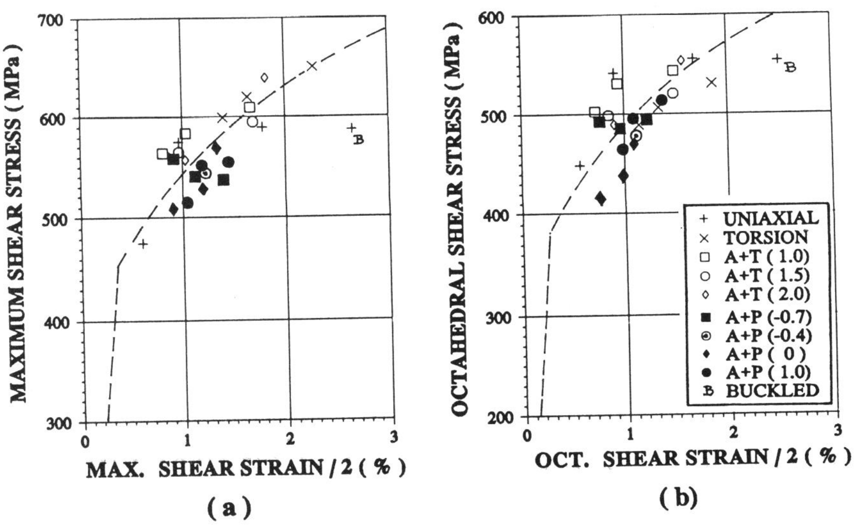
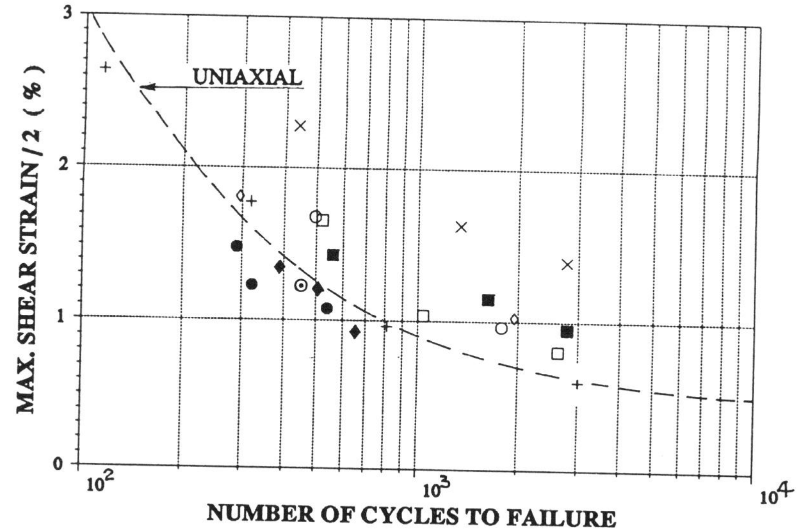
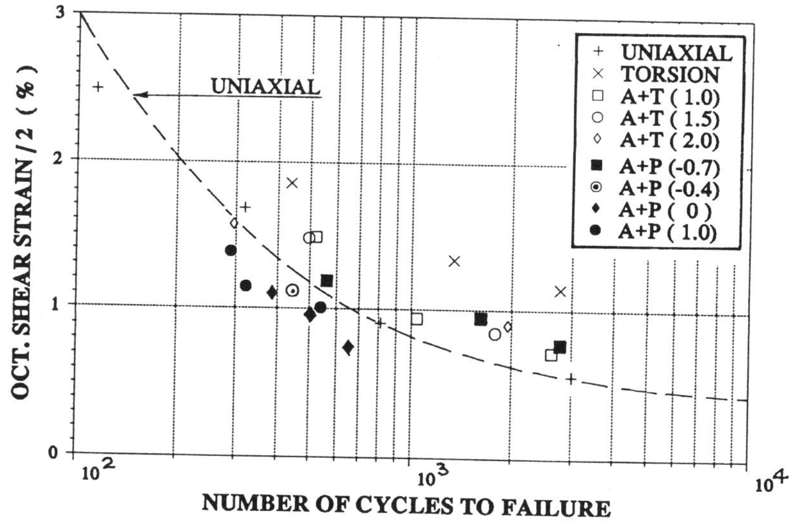


Fig. 2. Cyclic Stress - Strain Curve
(values of α and β shown in key)



(a)



(b)

Fig. 3. Fatigue Endurance Results
(values of α and β shown in key)