Low-Cycle Biaxial Fatigue Testing at Elevated Temperatures

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The Author, with co-workers (1)(2), has devised a biaxial fatigue machine and used it for strain-controlled tests at room temperature giving lives in the range 100 - 100 000 cycles. The specimens used were cruciform-shaped, each with a central region reduced in thickness and were loaded on all four arms by double-acting hydraulic cylinders. Electric resistance strain gauges have been used as strain transducers to provide the feed-back signals for the servo-controlled loading systems. Alternatively by signals from load cells, one for each direction, the tests can be load controlled. The strains in the two principal directions were independently controlled so that any ratio of strain amplitude and any phase difference was possible. The central region had to be designed to prevent buckling under compressive loads.

This method of testing differs from most other biaxial work in that it uses flat specimens. Some other workers have used cruciform specimens (3), but only applied tensile loads in each direction, thereby avoiding buckling due to compressive loads. The only other method by which all possible strain ratios can be tested on one form of specimen is by the use of tubular specimens with combinations of loading from axial thrust, torque and internal or external pressurisation (4)(5).

The Author's method has been reliable at room temperature only insofar as the basic resistances of the strain gauges do not drift. Since there is a drift of gauge resistance under repeated reversals of high strain, it has been necessary to control the amplitude of the alternating load so that the strain amplitude remains at the desired value, but the mean load rather than the mean indicated strain is kept at zero. This assumes that although the zero value of the gauge drifts, the gauge sensitivity does not vary.

The general success at room temperature prompted the Author to consider how the method could be used at higher temperatures. There are three main difficulties to be overcome: heating the specimen, measuring the strain and observing the progress of cracking.

The central region of the specimen needs to be maintained at a high temperature without the rest of the rig becoming hot. Hence water-cooled jaws are necessary and the region that can be occupied by the furnace is necessarily small. It was decided that the first materials to be tested should be steels used in steam power plant and that they should be tested at the normal working temperature for high pressure steam, i.e. 565 °C. The specification for the furnace was drafted to include the limits on physical dimensions and a maximum working temperature of 600°C. The furnace used, designed and constructed by Donaldson Furnaces, Ltd., comprised two halves, each containing an annular resistance heating element, which are clamped over the specimen. There is sufficient clearance for the loading arms to be unimpeded and for the transducer extension arms, which are described below, to move freely. The furnace is supplied with power from a West Gardian potentiometric three-term controller, the control signal being operated by a thermocouple attached to the central region of the specimen. Each half of the furnace has a central hole to permit radiant heat loss from the centre of the specimen which is normally at the highest temperature.

Tests have been conducted on a specimen with a number of thermocouples attached to it and with each arm gripped in a water-cooled jaw. When the furnace was controlled to maintain the centre of the specimen at 500 °C, it was found that at 6 mm from the centre the temperature was 487 °C. By introducing a fine air jet from a compressed air line on to the central region, the variation could be reduced to 5 °C. This uniformity of temperature is thought to be satisfactory. A steady temperature of 600 ± 1 °C has been maintained for long periods.

The only method of strain measurement that seemed feasible at these temperatures was by external transducers connected to gauge points on the specimen by extension arms. Here geometrical limitations were severe. It was essential that the gauge arms were not secured to the specimen by recesses which would cause strain concentrations and hence premature failure. The scheme adopted was to leave four pillars in the central recess on each side of the specimen (Fig. 1). The pillars lie one in the direction of each arm at 6·35 mm from the centre. They are smoothly blended into the recessed surface, for which a parallel-sided central region has now been adopted. Small holes are drilled in these pillars using a jig so that the holes are spaced 12·7 mm apart in each direction and holes on opposite faces of the specimen are exactly opposed. It is hoped that the relative movement of the tops of the pillars is a sufficiently accurate measure of the mean strain in the flat region. The central profile of the specimen is produced by spark erosion machining. Using a Metals Research Ltd. Servomet machine, one side can be machined from a flat surface in a day. As the final profile is approached, slower cutting rates are used so that the final surface has a finish good enough for satisfactory high-temperature fatigue tests. As the spark-machined surface is only as good as the surface of the tool, the tools used in the machining process need frequent refacing.

Transducer extension arms (Fig. 2), made from Inconel,

are clamped to the pillars by 10 BA stainless steel screws which have conical pointed ends. The screws are tightened until the arms are sprung slightly apart and secured in position with locking nuts. This permits rotation of the arms about the axes of the holes but does not allow lateral movement.

At their inner ends, the extensometer arms are shaped so that the two pairs, one for each direction, do not interfere with one another and leave as much of the specimen surface as possible unobscured for optical inspection. At their far ends they are spaced by light leaf springs. One arm carries the coil and the other moves the core of a Schaevitz miniature L.V.D.T. model 005MS-LT. The direction of relative movement of core and coil is parallel to the gauge length. Although the L.V.D.T. is housed outside the furnace and adjacent to a water-cooled coil, the type chosen is said to be capable of operation at temperatures up to 450 °C and so should be unaffected by such heat as may reach it.

Each L.V.D.T. is fed with a 2·5 kHz carrier wave from an Electro-Mechanisms CAS 2500 carrier amplifier which also gives a D.C. output related to the core position. With full gain of the amplifier, the sensitivity is 1 V for 0·05 mm displacement, i.e. 2·5 V for 1% strain. This is ample sensitivity for the servo-control drive and for operating plotters. The calibration is linear for a displacement range of about 0·35 mm, i.e. for a strain range of up to 3%. If we require to test at larger strain ranges, L.V.D.Ts. of lower sensitivity and greater linear range will be needed.

The standard procedure is to calibrate before each test. The transducer assembly is put on to a calibrating rig whereby relative movement of the transducer arms is controlled by a large barrel screw micrometer. The amplifier and plotter gains can then be set to the requisite values. The transducer assembly is then transferred to the specimen.

In initial setting up, the core has to be positioned correctly in the longitudinal direction relative to the coil. When on the specimen, the final adjustment to bring the core to the null position is made by the screw at the far end of the coil arm. This operates against two small springs which maintain the point of the screw in contact with a p.t.f.e. pad clamped to the cooling coil. P.t.f.e. is used in the hope that longitudinal friction will be so small that there is no restriction on the relative movement between the arm and the jaw.

At room temperature, crack detection has been by continuous observation of both sides of the central region of the specimen with optical microscopes. Hopes to use ultrasonic methods of crack detection have not materialised due to difficulty of continuous excitation and detection of ultrasonic waves at high temperatures and to the restrictions of space. For the high-temperature tests, microscopes with long-range objectives will be used to view the specimen through the holes in the sides of the furnace. At the temperatures to be used, there is enough radiant light from the furnace for illumination purposes. It is obvious that one will not be able to detect cracking at such an early stage as is possible at room temperature. Nevertheless, correlation of different tests can be made for various stages of crack propagation.

In other respects, this high-temperature fatigue machine is similar in design to the earlier one for room-temperature testing. Oil at a pressure of 20 N mm^{-2} is supplied from a hydraulic power pack. A control cabinet houses the amplifiers, servo-control circuits, cycle counter and other electrical equipment. A number of safety devices are incorporated. Any malfunction of the hydraulic supply, excess load or excessive movement of the jaws causes immediate shut-down.

At the time of writing, the complete assembly is just fully operational. Results of tests will be presented at the Congress.

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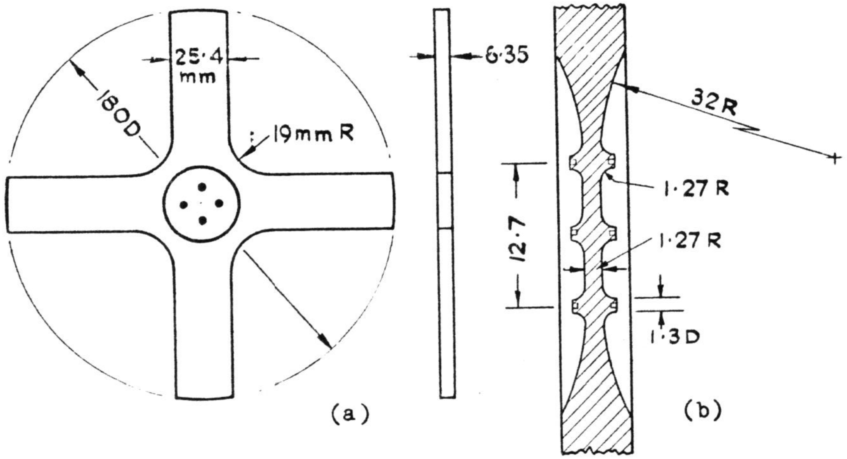

Fig. 1. (a) View of complete specimen. (b) Cross-section of central region - full size. Dimensions in mm.

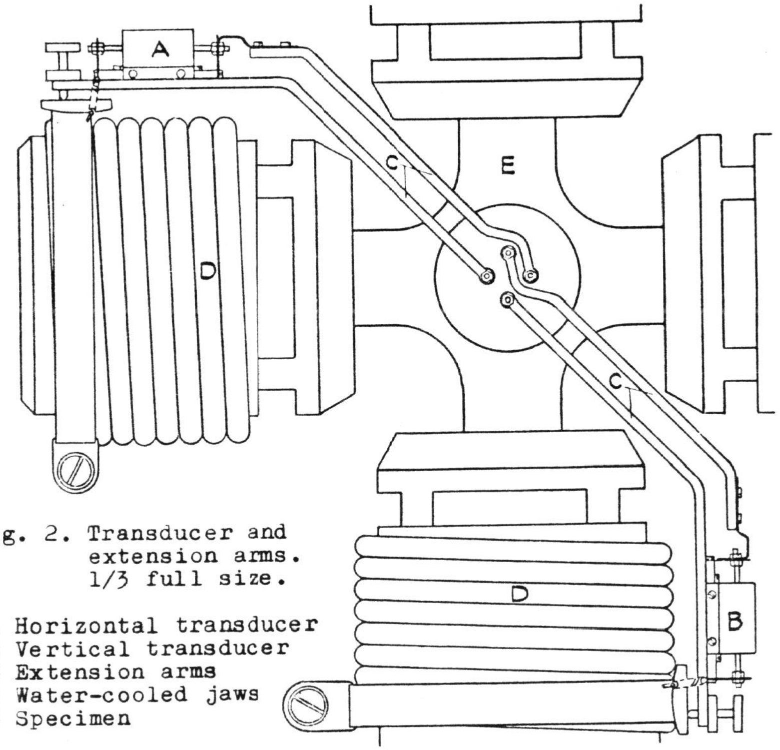

Fig. 2. Transducer and extension arms. 1/3 full size.

A Horizontal transducer
B Vertical transducer
C Extension arms
D Water-cooled jaws
E Specimen