*R. Stegmeyer**

The Design and Operation of a Test Facility for Temperature Cycling of Large Specimens

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ABSTRACT Thermally loaded components suffer cyclic strains due to changes in temperature. It is intended to investigate the crack initiation behaviour of such components, with special reference to shafts of large diameter. A testing facility was developed in which thick-walled hollow cylinders can be exposed to temperature cycles that simulate the start-up and shut-down of turbines.

With special clip-gauges, it was possible to determine the strain behaviour of the large specimens. Temperature and strain were recorded and processed on-line by a computer. Crack initiation was detected by magnetic particle inspection.

Introduction

During in-service operation of thermally-loaded components, the greatest loads occur during start-up and run-down and they create alternating strains resulting from the temperature changes. Furthermore, notches, essential to the design of components, produce an increase in the extent of alternating plasticity. The temperature-induced strains are of a multi-axial nature. Figure 1 shows typical strain and temperature curves for the surface of a turbine shaft.

For a considerable time, detailed studies have been conducted on the low-cycle-fatigue areas that suffer strain amplitudes beyond the elastic limit. These studies have been concerned with major influential variables and inter-relationships such as cycle time and cycle form, surface properties, notches, temperature, and hold times. Figure 2 shows a schematic summary of studies conducted up to the present time at MPA, the results of which are provided in references (1)–(5). All these experiments were carried out on small test rods with mechanically applied strains at constant temperature. Temperature gradients were avoided in the specimens. The application of results obtained with small specimens to large components is, however, always subject to uncertainty as to whether the adopted procedure is justified. In order to clarify this question, experiments were carried out with thick-wall hollow cylinders which were subjected to alternating temperatures. For this purpose, it was necessary to develop and construct a special test facility. Figure 3

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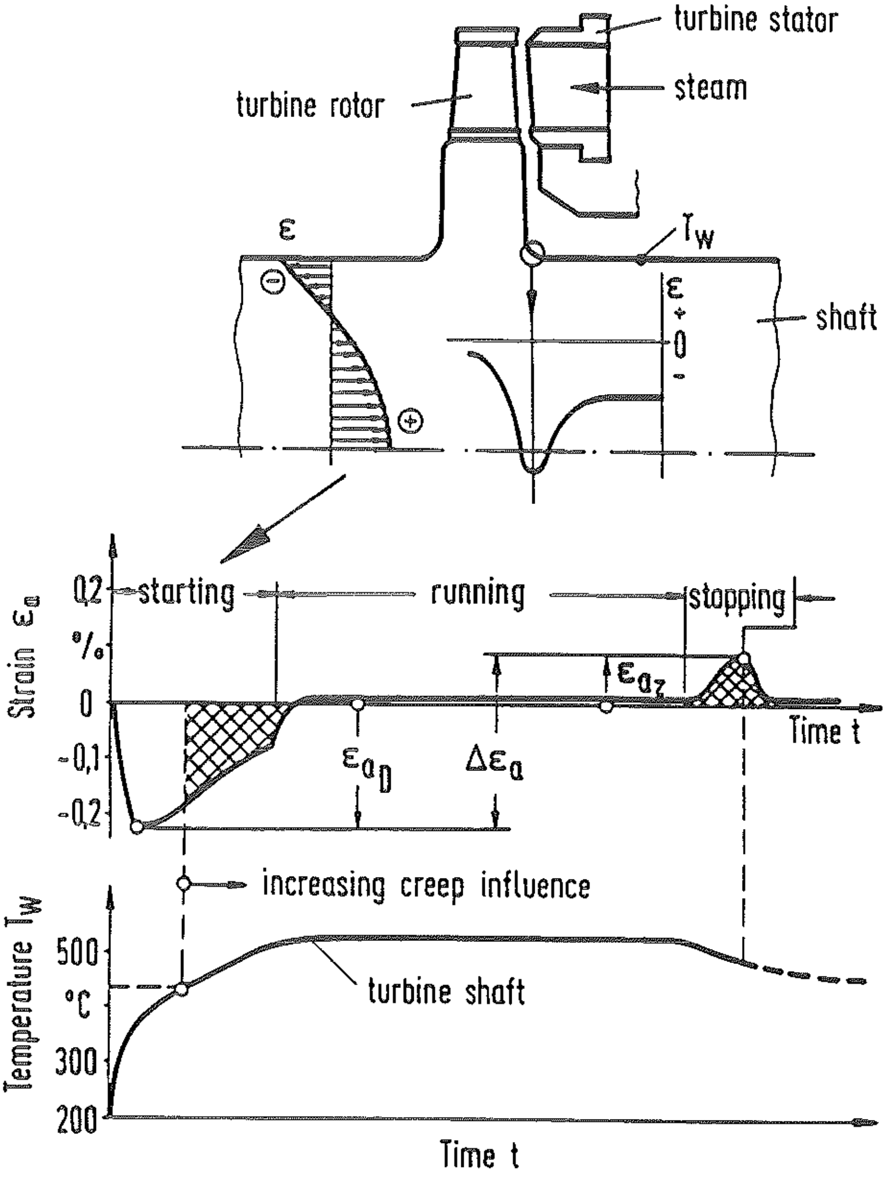

Fig 1 Typical strain and temperature behaviour of a turbine shaft

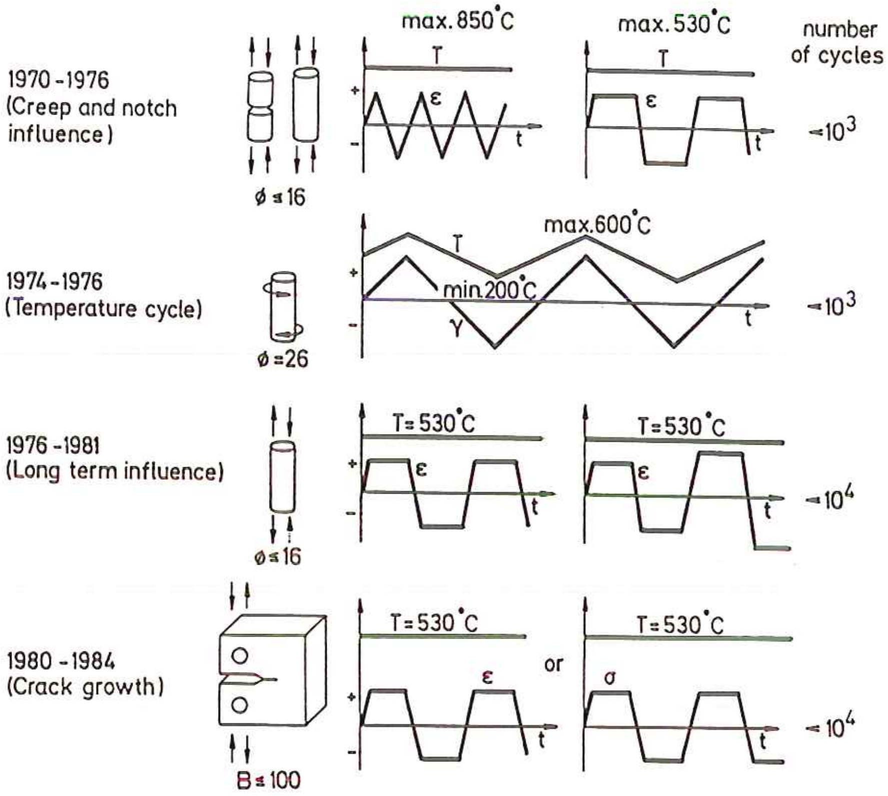

Fig 2 Schematic summary of studies conducted up to the present at the MPA

indicates the dimensions of the specimens used; circumferential notches were used both to obtain high strain levels and to facilitate the location of incipient cracks.

Experimental assembly

The intention was to achieve the temperature cycle shown in Fig. 4, which is based on the actual temperature profiles of a turbine shaft, Fig. 1, but accelerated with respect to time. It was, therefore, necessary for the test stand to incorporate the following features, (i) external heating of the specimen, (ii) internal cooling of the specimen, and (iii) external cooling of the specimen.

The test stand was required to make provision for variable hold times, different limit temperatures, and different heating rates. The upper limit temperature was, however, specified at 530°C, based on the operating data for a steam power plant. Specimen heating is carried out inductively via the outer

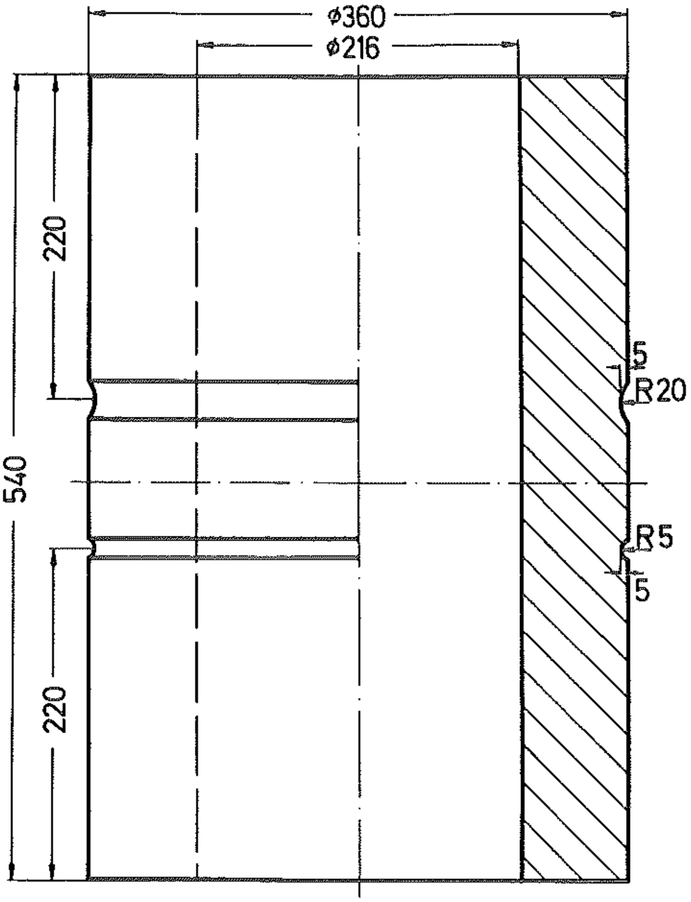

Fig 3 Specimen geometry (dimensions in mm)

surface. Depending on the rate of heating, a more or less steep temperature gradient can be obtained; this gradient can be increased by simultaneously cooling the inner wall. Once the maximum temperature is reached, a steady state is established, while retaining the inner/outer temperature difference. After the inner cooling is switched off, temperature equalization takes place at 530°C. Subsequent external cooling produces an inverted temperature gradient. By means of this temperature cycle, it is possible to produce alternating strain at the base of the notch of the model by purely thermal cycling.

A schematic of the test stand is shown in Fig. 5(a). In the centre of the assembly, the specimen is enclosed by the inductor. The internal and external cooling is also indicated.

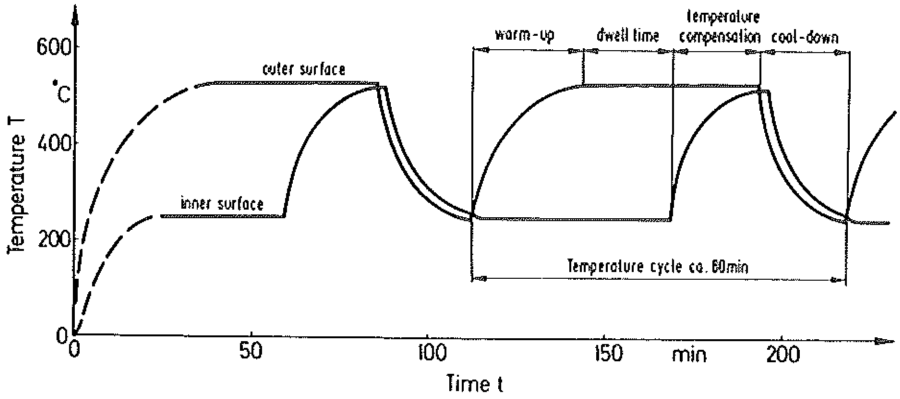

Fig 4 Schematic temperature cycle, based on the actual temperature characteristics of a turbine shaft

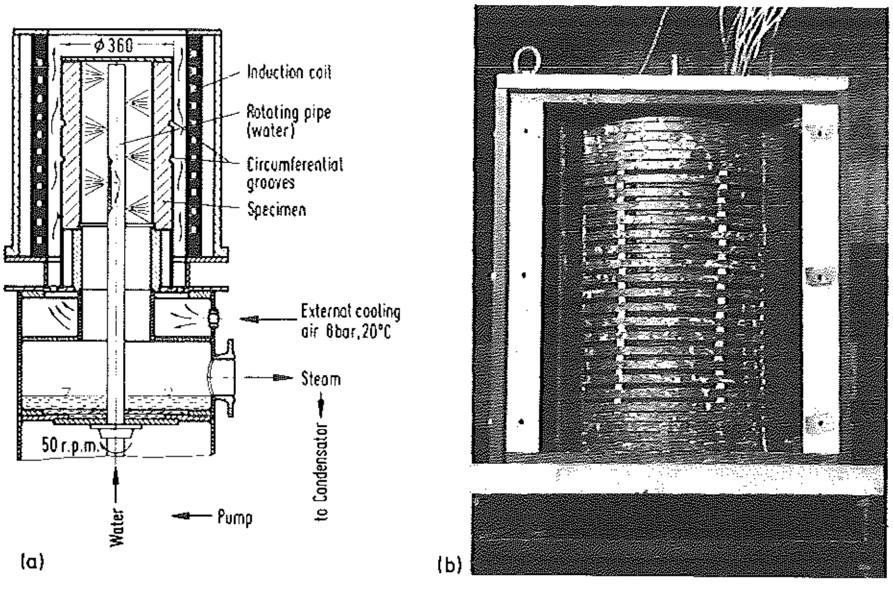

Fig 5 The test stand: (a) principle of the test stand; (b) test stand with induction coil

Heating

A choice of various heating systems, such as convection, radiant ovens, and inductive heating, was available for the heating of the model. In order to simulate the thermal strains in the specimen, however, it was necessary to achieve accelerated heating, which was possible only with inductive heating by enclosing the specimen with coils of water-cooled copper tubes. Alternating current produces an alternating magnetic field in the coil. In accordance with the law of induction, and the specimen acting as a single winding, a powerful current is produced at the surface of the specimen, thus creating a heating effect. Preliminary experiments showed that a power input of 150 kW (power output 135 kW) was sufficient, and that a frequency of 3000 Hz produced the best temperature distribution.

Final optimization of the inductor was carried out after production of the assembly at MPA. Initially the temperature profile during the heating phase decayed towards the ends of the model, but this was almost completely counteracted by varying the distance between the windings of the inductor (Fig. 5(b)). However, as the hold time is increased (maintenance of the temperature difference across the wall thickness), this temperature drop establishes itself once again. If the winding was positioned in such a way as to obtain a constant temperature profile during the hold time, the temperature drop was shifted into the heating-up phase. Since the experiments are concerned with fatigue characteristics, and the distances between the windings can, therefore, not be changed during the duration of the experiment, particular emphasis was placed on obtaining an even temperature distribution during the heating-up phase. It was not possible to detect an influence of the penetration depths of the heat sources on the temperature gradient. Finally, it was noted that there is no effect on the alternating strain behaviour of the specimen due to the penetration depths since the strains at the surface are determined by the global deformation of the specimen.

Internal water cooling

The internal cooling of the specimen at first presented considerable difficulties. Special modifications were necessary to ensure that the experiments ran smoothly. The least expensive cooling method, and the easiest to handle under experimental conditions, was direct spraying of the inner wall surface with water. Water at a temperature of 80°C (the water temperature stabilizes after the start-up cycles) is fed from a tank by means of a high-pressure pump (20 bar) into a nozzle assembly. The inner surface of the specimen is sprayed with water by flat nozzles arranged at constant intervals along the rotating (50 r/min) axis of the nozzle assembly. The water flow rate is controlled by a solenoid valve connected upstream of the nozzle assembly. The solenoid valve is fed with pulses from the programme control, which compares the thermocouple voltages from the inner surface of the specimen with a predefined level. The

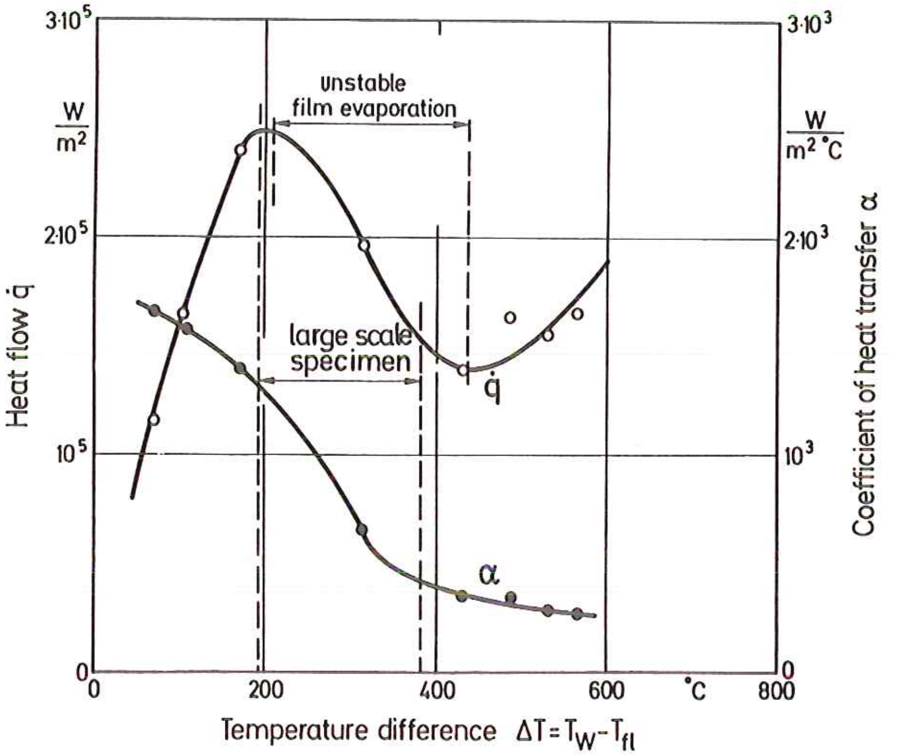

Fig 6 Heat flow coefficient of heat transfer as a function of the temperature difference

vapour produced during cooling is liquefied in a condenser and returned to the water tank. Slight vapour leakage losses are compensated by means of a float system in the water tank from a supply tank via a solenoid operated valve. The inner wall temperatures achieved with this cooling system were between 180 and 200°C, with negligibly small temperature differences. The intention was to use higher inner wall temperatures (greater than 200°C), which reduce the temperature gradient across the wall in order to obtain longer running times to the point of incipient cracking. Plots of time/temperature curves, however, indicated that this led to the loss of the homogeneity of the temperature field. Parallel experiments, involving the spraying of a flat vertical plate showed that, at these temperatures, a further thermodynamic effect, namely unstable film vaporization, is also significant. Figure 6 shows an evaluation of the plate experiment. Unstable film vaporization occurs in the temperature range between 200°C and 450°C. This produces locally varying heat-transfer coefficients and it is no longer possible to control the cooling loop. The nature of the surface is a further difficulty in obtaining adequate control.

The remedy to these problems was to keep the inner wall temperature below

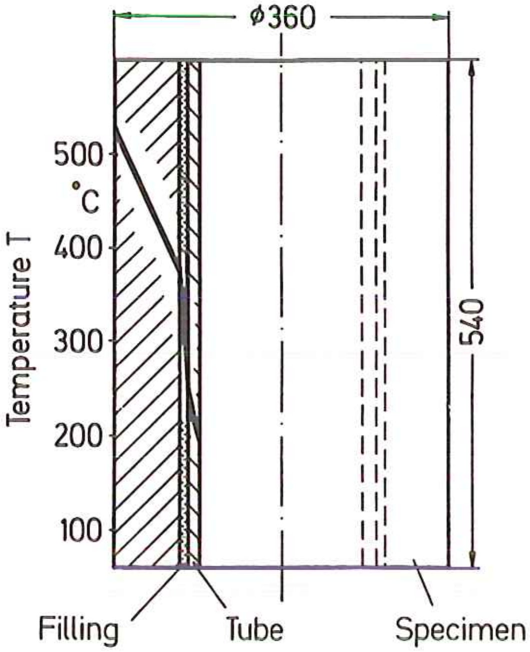

Fig 7 **Schematic temperature gradients, built up by a fictional increase in the wall thickness**

the film vaporization temperature, i.e., to increase the wall thickness of the specimen while keeping the outer diameter constant. This made it possible to obtain a flatter wall temperature gradient in the specimen. The greater wall thickness will, however, also increase the load in the outer skin of the specimen. This effect can be avoided by making only a fictive change in the wall thickness of the specimen. If the inner diameter of the model is reduced by means of a tube, and if the resulting annular gap is filled with a good heat conductor, the temperature at the inner side of the specimen shifts in the direction of higher values. The effect on the temperature gradient is shown in schematic form in Fig. 7. As long as the deformation of the model is not impeded by the additional tube, this measure has an influence only on heat conduction and not on the mechanical behaviour of the specimen. The medium chosen for heat transfer was a tin/lead alloy, whose melting point is 220°C.

External air cooling

After heating to 530°C, the specimen is cooled via its outer surface by means of air. A high-pressure blower is available for this purpose, with a delivery of 2000 m^3 hour. The air delivery is evenly distributed by means of an annular duct in the experimental assembly and air flows past the specimen from bottom to top through rings of drilled holes. This produces a slight temperature gradient along the specimen, which gradually increases with time.

Instrumentation

Temperature measurement

Temperature measurements were recorded by Ni–Cr/Ni thermocouples. Measurements were taken not only at the surface but also inside the wall. This was achieved by means of bore holes of various depths in which thermocouples were placed. The thermocouples were secured by spot-welding them to the specimen. In order to obtain precise data concerning the temperature distribution in the circumferential and longitudinal directions and across the wall thickness, the first specimens were fitted with up to 60 thermocouples; Fig. 8. Because of the large number of thermocouples, consideration was given to the use of a Compulog IV measurement system. This was used initially as a 'stand-alone' system, but was later coupled to a computer system to allow a better and more rapid evaluation. The measuring devices for strain and temperature fed their signals directly into Compulog and the data was then stored in a PDP 11/44. Data could be selected and graphically presented from a VAX 11/780. Measurement with the Compulog system offers the further advantage that an integrating measuring method is used, thus filtering out superimposed oscillatory interference; e.g., from the heater induction circuits.

Attempts to measure the temperature directly at the inner wall surface of the model were unsuccessful, due to the fact that a thermocouple indicated an undefinable value between the water and wall temperature. The inner wall temperature was, therefore, measured as a general principle via an external bore 2 mm from the inner wall surface.

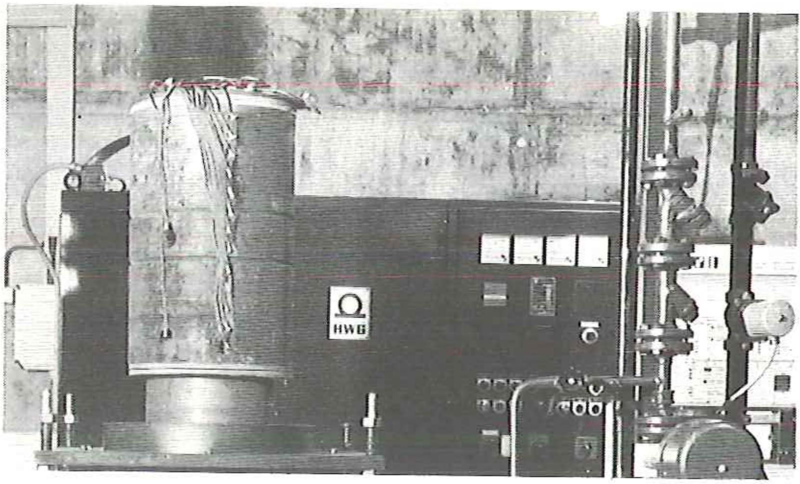

Fig 8 Specimen fitted with thermocouples

Strain measurement

The success of the experiments as a whole depended on measuring the longitudinal and circumferential strains at the notches and at the smooth surface. From the instrumentation point of view, it was realized that considerable difficulties would be encountered due to the high and varying temperatures and the small notch radii ($R \leqslant 5$ mm). Commercially-available displacement pick-ups (clip gauges) prove to be unsuitable by virtue of their size, making it necessary to develop transmitters especially adapted to this problem. In designing the displacement pick-up, use was made of the fact that conventional foil strain gauges represent an excellent measuring device at room or slightly higher temperatures; however, they must be cooled for use at higher temperatures. This is achieved by applying the strain gauges between a water-cooled cold bridge. Due to this cooling, the operating temperature never exceeds 40°C, despite an ambient temperature of 530°C. The blade gap of the pickup is 3 mm. To allow use as a strain gauge, a high resolution is required for the measured displacement. The geometrical shape was optimized by means of finite element calculation.Reliable measurements can be obtained of 2/10 000 mm. Figure 9 shows this pick-up, while Fig. 10 shows the actual application of four pick-ups of this kind. The pick-ups are calibrated on a micrometer device, with a resolution of 0.001 mm, via the measurement system described previously. During the adjustment of the strain gauges, the blade gap is optically measured. After the gauges are secured to the specimen with heat-resistant springs, the initial blade gap required to calculate the strain is determined mathematically. The impeded strain (i.e., the total strain minus pure heat expansion) is calculated and represented by the temperature and the associated coefficient of thermal expansion ($\alpha = f(T)$) on-line. The temperature is measured synchronously on the model.

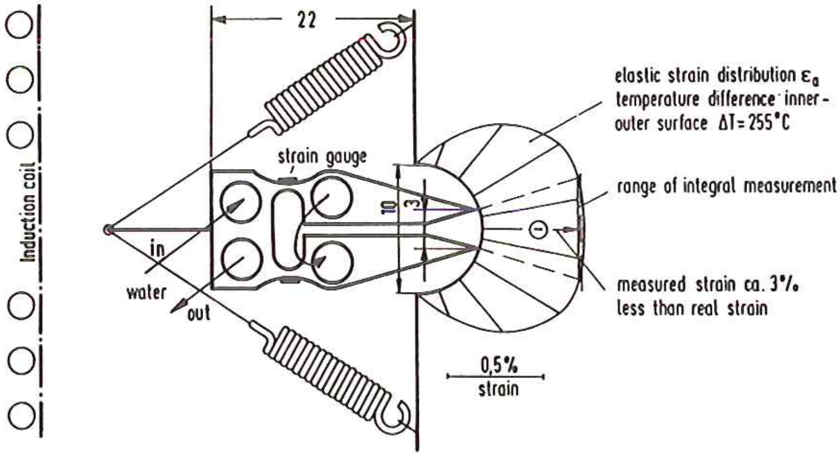

Fig 9 Geometrical data of the water-cooled clip gauge

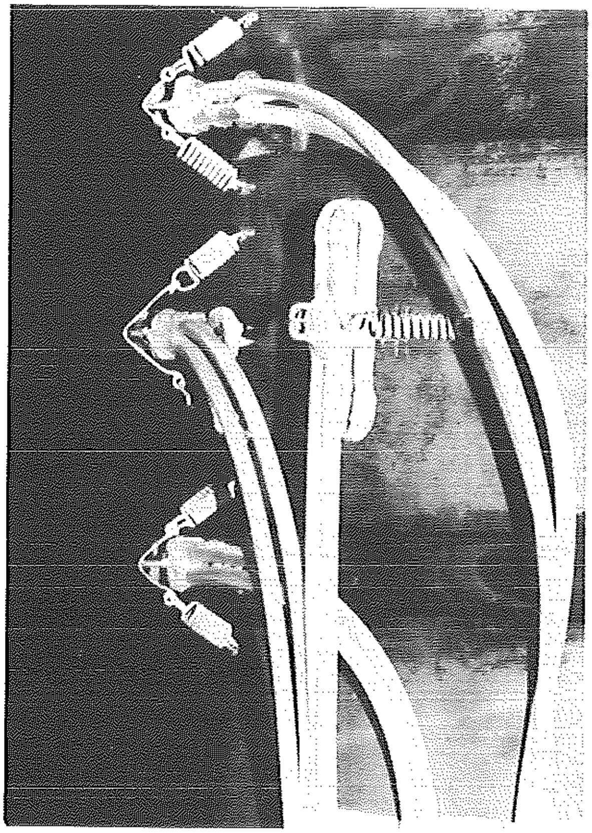

Fig 10 Water-cooled clip gauges applied to the specimen

Incipient crack detection

In order to compare the larger-scale specimen and smaller specimens subjected to axial load at a constant test temperature with regard to the number of cycles required to produce incipient cracking, the time to incipient cracking must be known as accurately as possible. Incipient cracking can be detected by the dye-penetrant method, or by magnetic particle (Magnaflux) inspection. Both these methods can be used only with the specimen in a cold state. It was possible to detect incipient cracking at an extremely early stage by successive removal of the first specimens or, once the first results were available, by estimating the relevant load cycle range and making subsequent periodic checks. With the Magnaflux inspection, it was possible to detect incipient cracks from a crack depth of 0.1 mm onwards, while the dye-penetrant method, this was possible only from approx. 1 mm or more. For this reason, preference was given to the Magnaflux inspection. After cooling the specimens were magnetized directly with the induction coil. In this case, only circumferential cracks can be detected.

Temperature cycles and distribution

Through the use of the solution involving the fictive increase in the wall thickness of the model, it was possible to match the lower limit temperature approximately to the desired strain amplitude while retaining the maximum temperature of 530°C. A total of five different temperature cycles were used. Figure 11 shows one of the temperature cycles which were measured. The temperatures around the periphery exhibit a maximum scatter of 5°C at the upper limit temperature of 530°C. A large number of measurements on the first specimen showed that the temperature gradient across the wall is virtually linear during heating and cooling; Fig. 12. The temperature distribution along the outer generating line of the specimen is shown in Fig. 13. The air flowing from bottom to top cools the lower third of the specimen more effectively. The temperature gradient so produced along the generating line disappears during the hold time or the heat-soaking period of the specimen. Accordingly, this has no influence on the following cycle.

Strain distribution

Following the development and testing of the water-cooled pick-ups, it was possible to use these on specimen No. 3 and onwards. Two clip gauges in each case allowed axial and circumferential strains to be measured at the notch base and on the smooth surface. In measuring the axial strain components in the notch base, however, it was necessary to make allowance for the fact that, with a small notch radius ($R = 5$ mm), it was not possible to fully measure the influence of the radius of curvature on the (local) maximum strain in the notch base using the integral measuring method; i.e., 3 mm measuring length of the

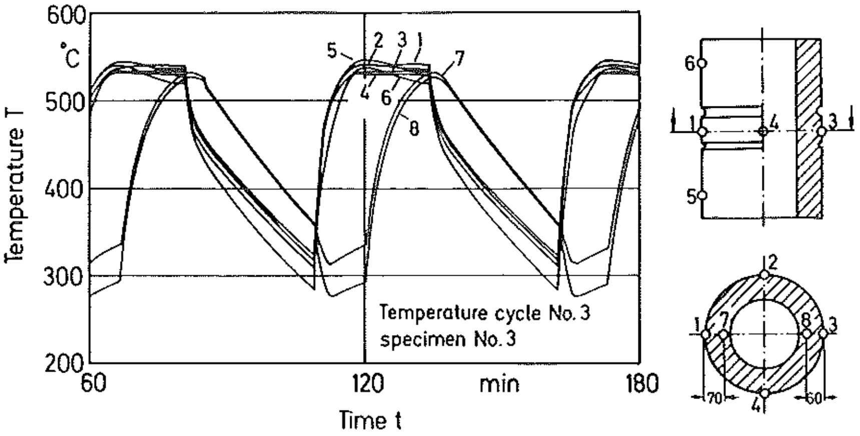

Fig 11 Temperature cycle No. 3

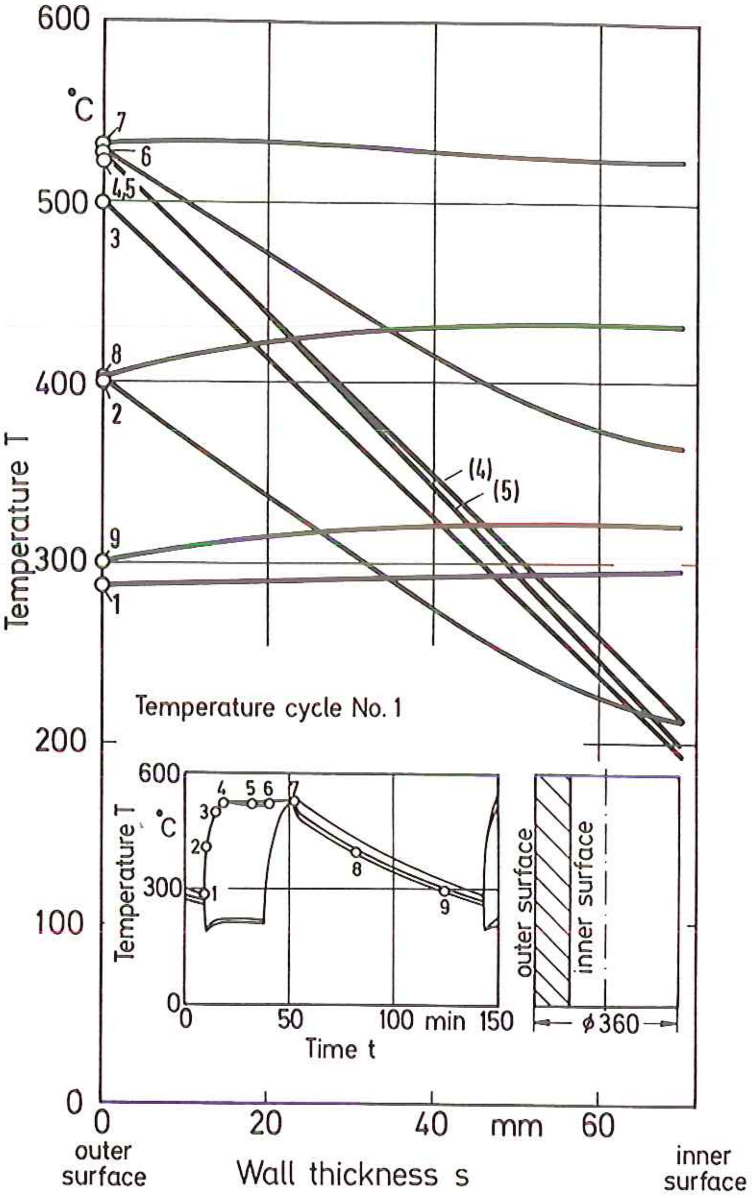

Fig 12 Measured temperature curves in the wall at various times within a cycle

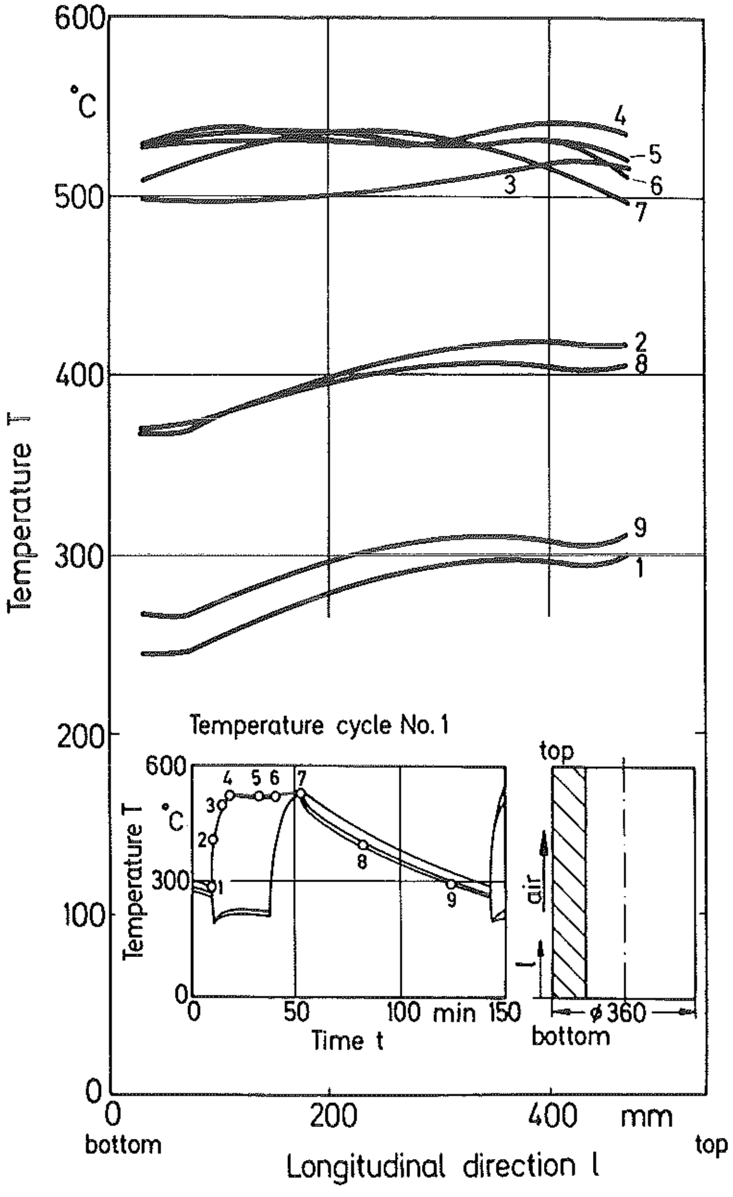

Fig 13 Temperature distribution along the outer generating line of the specimen

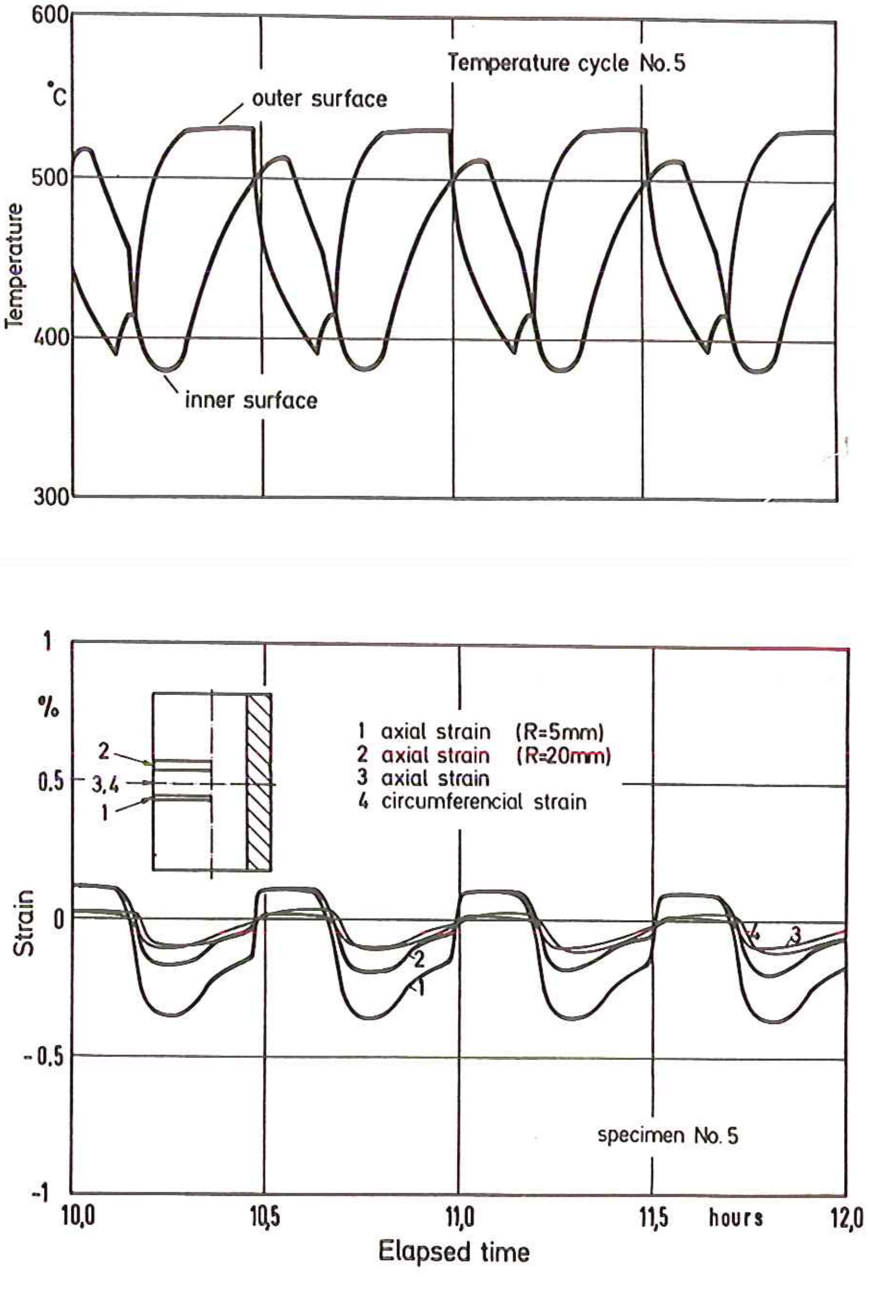

Fig 14 Correlation between the strain curves and the temperature curves

displacement pick-up; i.e., the strain measured with the displacement pick-ups in the notch base is smaller than the maximum strain. Elastoplastic calculations carried out for this purpose using the finite element method indicated a difference of approximately 15 per cent between the theoretical (maximum) and measured (integral) axial strain, for which allowance has to be made in the evaluation. Figure 14 shows the correlation between the strains and the temperature present for each case. Theoretically, the axial and circumferential strains measured at the undisturbed surface should be identical. The slight differences which can be seen in the figure are negligibly small, and lie within the resolution range of the displacement pick-ups.

Summary and conclusions

In order to investigate the applicability of experimental results on small laboratory specimens to components subject to multi-axis thermal load, a turbine shaft was selected as a relatively simple axisymmetric component, and this component was modelled by means of a test specimen. Design-related shape deviations such as shaft shoulders, grooves, etc., were simulated by means of circumferential notches. A specially-designed experimental assembly made it possible to subject the large-scale specimens to alternating temperature load, such as those that occur at the start-up and run-down of turbines. Furthermore, by varying the notch radii, it was possible to vary the strains produced by the temperature gradients in the notch base. The fictive wall-thickness enlargement of the specimen by means of an inserted tube allows the inner wall temperature to be adjusted as desired. Following the development of special water-cooled displacement pick-ups, it was possible to determine the strain characteristics of the specimen as a function of temperature.

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