A VIBRATING REED TECHNIQUE FOR "HE STUDY OF CORROSION FATIGUE IN GEOTHERMAL STEAM

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ABSTRACT

The principles and operation of a method to study corrosion fatigue behaviour in geothermal steam is described. The system utilises separated steam at 10 bar pressure to excite resonant vibration in a reed specimen of test material. The high frequency and precise stress amplitude control provides for fatigue endurance data to be accumulated more rapidly and with a higher degree of reliability than was possible using the conventional rotating bending technique. The sensitivity of the resonant frequency to the onset of metallurgical changes within the specimen has enabled crack initiation to be identified and crack propagation velocity to be derived. The use of the facility to terminate fatigue tests in the early stages of crack development has made it possible to study incipient fracture surfaces by high resolution electron microscopy.

The free vibration of the system lends itself to amplitude decay methods of damping capacity measurement. The engineering and metallurgical significance of these data is discussed with particular reference to the mechanism responsible for corrosion fatigue crack initiation.

INTRODUCTION

A major limitation on the performance of steam turbines is imposed by the potential for blade failures to occur due to high cycle fatigue. This constraint on turbine design is further compounded in geothermal applications by the aggressive nature of the steam which promotes a more highly accelerated failure mode, that of corrosion fatigue.

The process causing fatigue failure is one of highly localized slip within the metal structure that occurs incrementally with each load cycle. The accumulated damage over millions of cycles results in the formation of a surface microcrack which eventually leads to component failure. The presence of a corrosive agent siqnificantly depresses the stress required to induce this process and once in operation acts to accelerate the progress of crack growth until final fracture. using a conventional rotating bending test method, the fatigue endurance limit of 12% chromium stainless steel turbine blade alloys have been found to be depressed 50% below the endurance value determined in air[1]. This loss in strength has been observed even over short periods of exposure to the steam and has occurred without any obvious surface corrosion having taken place. Observations of the fracture surface generated under these conditions has revealed crack propagation behaviour radically altered from that produced by the fatigue process in air.

Thus the combination of cyclic loading and geothermal steam produces failure along preferred paths within the microstructure of the stainless blading alloys. The reason for such selective attack and the extent to which this is influenced by the microstructure and range of strength levels, obtainable in these alloys became a matter of some interest. The solution to this and other questions posed by geothermal corrosion fatigue behaviour required more than just the 'survival' or 'failure' result derived from the conventional testing method. The vibrating reed system was therefore developed to its present level in order to provide the flexibility demanded by the experimental series.

The basic principle of the vibrating reed is not entirely new, various forms of pneumatic excitation have been used on occasions to study frequency effects, particularly in the aviation industry. The application of the technique to geothermal steam, however, results in a self contained system in which the steam provides both the excitation source and the environment for study. The high speed and precision of control will provide more rapid, reliable results on a number of different aspects of the fatigue process. The availability of modern transducers and microprocessor based monitoring facilities has resulted in a degree of experimental flexibility in the field only obtainable in complex and expensive laboratory based equipment.

OPERATING PRINCIPLES

The basic components required for the system are a steady steam supply with fine admustment flow control, an amplitude measurement system and a specimen vibration chamber. Figure 1 shows a schematic layout of the equipment that has been

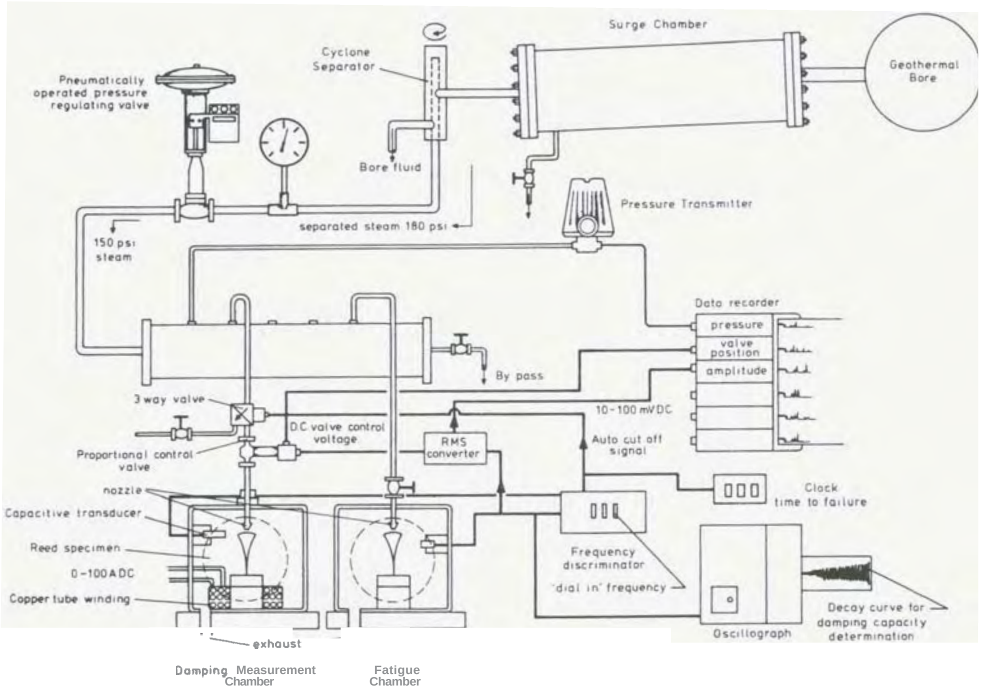


Fig. 1 Schematic Layout of the Reed Fatigue System.

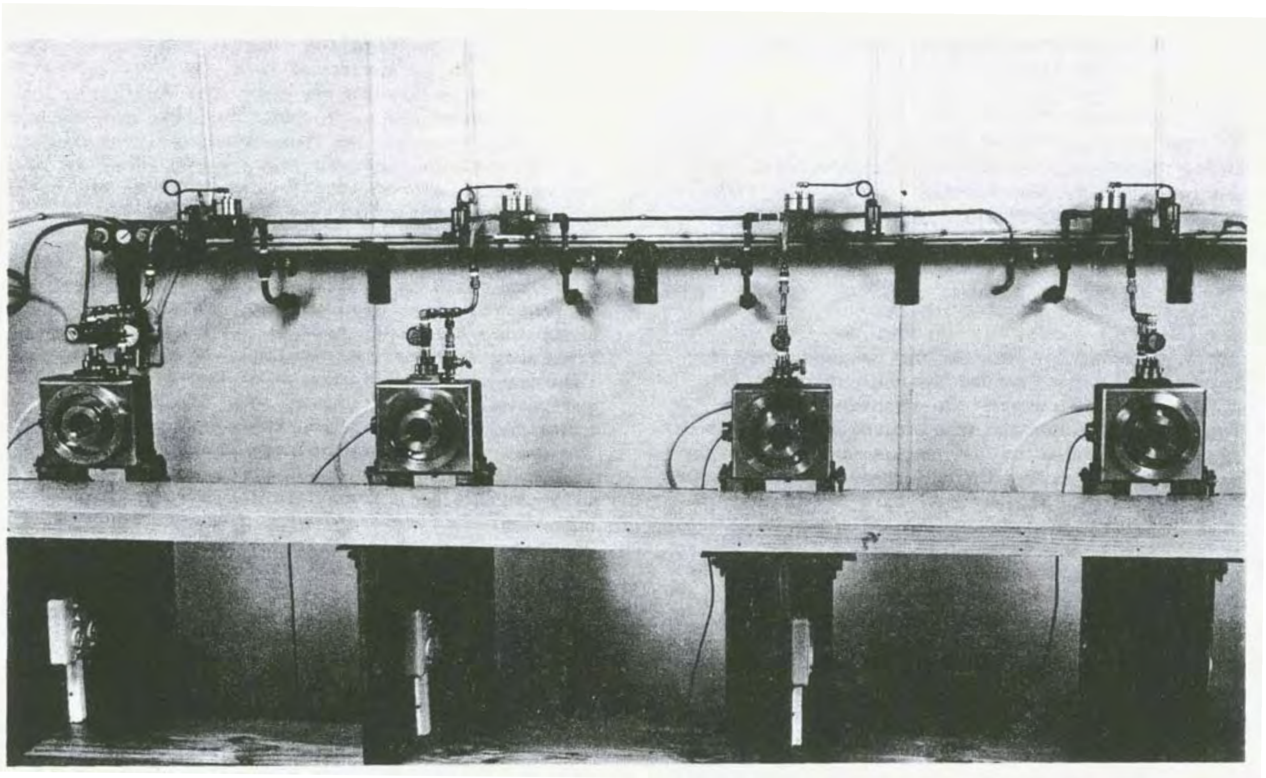


Fig. 2 Testing Chamber and 3-way valve layout.

installed at the Bore 22 site in the Broadlands field. A two phase flow is taken from the bore and passed through a surge tank and cyclone separator. The resulting steam is passed through a pneumatically controlled pressure regulating valve which maintains a continuous 10 bar pressure in the manifold to within 5.02 bar. In order that this stability be maintained during specimen changes, a constant steam demand on the manifold is established. This is achieved by a 3-way valve which directs steam either to the test chamber or to exhaust throuqh a matching orifice. In this way a test can be terminated by automatic actuation of this valve thus preserving the specimen from further exposure or damage.

The reed specimen is located in a vice clamp positioned on the centre line of the steam nozzle. The impingement of the steam flow on the end of the specimen induces vibration at a resonant frequency characteristic of its size and geometry. A typical frequency of 320 Hz is generated by the dimensions 50 mm length x 15 mm wide x 0.6 mm thick that have been selected for the current testing programme.

The major controlled variable in fatigue testing is that of cyclic stress. In the reed system this is controlled by the fine adjustment valve upstream of the nozzle and is measured from the tip of the specimen by a travelling microscope using fibre optic illumination. This test system is duplicated in four vibration chambers mounted in line against the microscope table as shown in Figure 2. The tip amplitude measurements taken during the setting up of a test are used to set real values of specimen displacement against the output of the magnetic inductive transducer, visible in Figure 3. The test amplitude is then selected in the form of a transducer output voltage which is then recorded and monitored, along with values of manifold pressure, throughout the duration of the test.

SPECIMEN PREPARATION

Testing material in the form of reed specimens has marked advantages from the preparation aspect in that large numbers of identical specimens can be manufactured at low cost and in the wide range of metallurgical conditions demanded by the experiment. The reeds are made from strip material cut into rectangular blanks and clamped together into stacks containing about 50 specimens. In this ‘block’ form the material is heat treated, quenched and tempered to provide the microstructure and properties selected for study. The block is then reduced to the desired dimensions and profiled by surface grinding. Individual specimens are then separated from the stack and finished by hand grinding and polishing.

CALIBRATION AND TESTING

In order to carry out fatigue tests, the relationship between amplitude and maximum stress must be determined for each material. This is

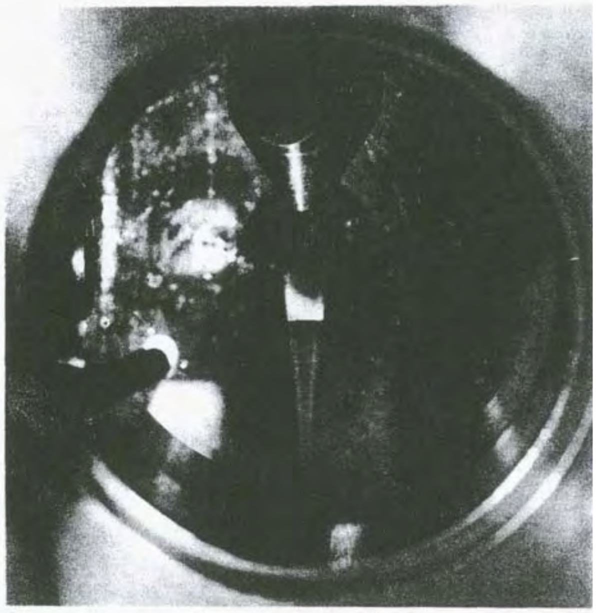


Fig. 3 Reed Specimen Vibrating at 320 Hz.

achieved by calibrating a single specimen under static and pneumatically excited dynamic conditions using miniature strain gauges. These are attached at the base of the specimen and allow measurements to be taken to relate values of stress and strain over the working range of the tip amplitude.

The endurance of each specimen is tested at a selected stress, the result of which contributes to the data represented in the form of a plot of stress vs number of cycles to failure (S/N curve).

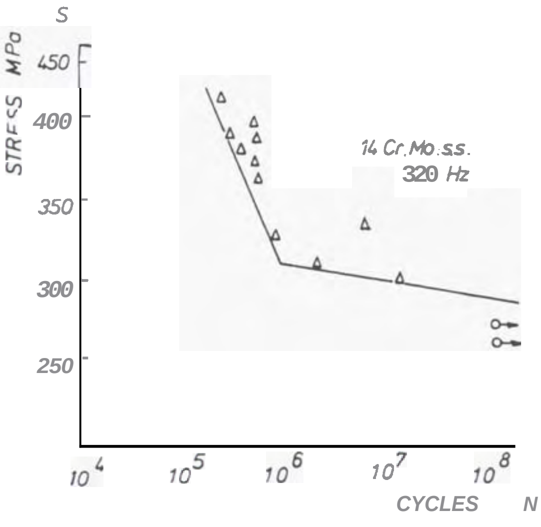


Fig. 4 S/N Representation of Corrosion Fatigue Data.

Since the frequency of vibration is constant within measurable limits (.03%) it can be used as an indicator of the onset of crack initiation. The resulting decrease in the resonant frequency can be used to actuate the 3-way valve resulting in the termination of the test at the desired stage. In this way undamaged crack surfaces are produced which can be subsequently examined by high resolution electron microscopy. Access to the crack surface is achieved by breaking open the remaining cross section using the brittle transition induced by immersion in liquid nitrogen.

RESULTS

The fatigue endurance data of a 14% chromium alloy derived from the trials of the system at Broadlands are shown in Figure 4. The S/N curve representation of this information characterises the corrosion fatigue behaviour of the alloy in this environment. From this curve the stress below which the material can be predicted to survive 10^8 cycles can be identified at 290 MPa and is designated the Fatigue Endurance Limit (F.E.L.). The results of corrosion fatigue tests are compared on the basis of this value and on the extrapolation of the line gradient to higher cycle values.

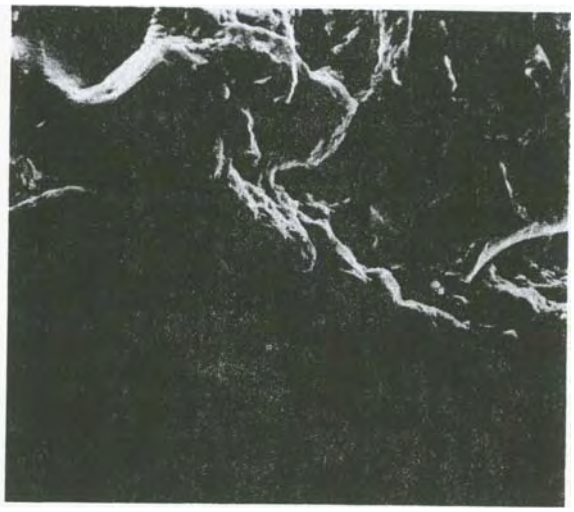
x 1000 mag.

Fig. 5 Predominantly intergranular fracture: stress, 366 MPa endurance, 8.4 x 10^5 cycles.

x 1000 mag.

Fig. 6 Transition of corrosion fatigue crack (bottom right) to brittle fracture (top left).

Fig. 7 x 1500 mag.
Oblique metallographic section through C.F. fracture, showing two phase structure of ferrite and martensite.



x 1500 mag.

Fig. 8 Evidence of grain boundary decohesion in advance of C.F. crack.

The fracture surfaces generated during these tests are shown in Figures 5 to 8. The limit of the corrosion fatigue crack front and its sudden transition to brittle fracture by cleavage can be seen in Figure 6. Evidence of the selective nature of crack propagation in geothermal steam is shown by the predominantly intergranular fracture surface. The influence of microstructure in this process may be examined by taking an oblique metallographic section through this area as shown in Figures 7 and 8. This reveals that in this two phase alloy, crack propagation in the proximity of the ferrite phase (dark) is restricted to the grain boundary whereas the boundaries of the martensite phase (light) are not as susceptible. An interesting feature of Figure 8 is the indication that the decohesion of grain boundaries occurs in advance of the propagating corrosion fatigue crack. Results of this type tend to suggest a failure mechanism based on the embrittlement of specific paths due to the action of diffusing gaseous species. More information on this behaviour and the effect of altering steam composition may be revealed by the development of a specific aspect of the reed vibration studies, that of residual damping capacity measurement.

POTENTIAL DEVELOPMENT

Damping capacity is a physical property that requires careful consideration in the selection of a suitable turbine blade alloy. The value of damping capacity, expressed by the log decrement (δ), describes the degree of energy absorption of the material during vibration. This property can be measured in the reed system from the amplitude decay profile resulting from sudden removal of excitation. This facility will be used to provide damping data for engineering purposes on a range of alloys and metallurgical conditions.

It has been noted by several workers that the onset of the early stages of the metal fatigue process can be detected by changes in damping capacity. Lazan[3] identified a minimum stress at which δ began to increase with the number of load cycles. This stress, designated the Cyclical Stress Sensitivity Limit (C.S.S.L.), was more accurately located for 12%Cr stainless steels by Willertz[4] by suppressing the magnetostrictive damping component. The means of producing the magnetic field required to perform such measurements in the reed system is shown in Figure 1. The specimen is placed in magnetic saturation by means of a water cooled solenoid, energised by a 100 A d.c. p e r supply. Vibration amplitude in this set up is measured by a capacitance type pick up since it is unaffected by the presence of the magnetic field. The output of this device is fed through an amplifier to a data processor where measurement and calculations on the free decay profile are carried out.

OBJECTIVES OF RESIDUAL DAMPING MEASUREMENT

The very low residual damping levels that are measured under conditions of magnetic saturation are an accurate indicator of the degree of damage being sustained by the crystal structure during stress cycling. If a consistent relationship can be determined between the stress producing recognisable changes in residual damping, (the C.S.S.L.), and the fatigue limit, then a means of predicting corrosion fatigue behaviour would have been produced. The ability to monitor these changes in a single specimen would enable direct measurements to be made on the reaction of a material to adjustments in steam chemistry. The development of a successful system of this type would have important implications both in the speed of acquisition of data and in the way that the subject of corrosion fatigue is researched.

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