FRACTURE TOUGHNESS TESTING OF A LOW ALLOY STEEL IN GEOTHERMAL ENVIRONMENTS

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ABSTRACT

The resistance of a steel to hyarogen assisted cracking is an important design parameter when choosing a steel for use in a geothermal environment. Hydrogen embrittlement arises because of the presence of hydrogen sulphide in the geothermal steam. Other types of environmentally-assisted cracking probably also occur especially at higher temperatures. The determination of fracture toughness using a fracture mechanics approach provides a material parameter, the stress intensity for onset of sub-critical cracking, K_{Iscc}, which is independent of specimen size and crack geometry. Therefore K_{Iscc} values found from exposures of test specimens to the geothermal environment can be used to calculate maximum design stresses and/or allowable flaw sizes for power station components which are to be subjected to the same environment. A program to determine the stress intensity for the onset of subcritical cracking, K_{Iscc} for a low alloy steel heat treated to different strength levels and exposed to Broadlands steam under simulated turbine conditions is described and discussed.

INTRODUCTION

A notable feature of electric power generation from geothermal steam in comparison with conventional and nuclear power stations is the largely uncontrolled chemical content of the steam. In conventional and nuclear power stations the steam supplied to the turbine is highly purified because it has been established that low concentrations of impurities such as carbonate, nitrate, chloride, alkali or hydrogen sulphide cause stress corrosion cracking of low and medium strength steels, (Carter and Hyatt, 1973). It has also been established (Roberts and Greenfield, 1979) that cracks can propagate in typical low alloy rotor steels in pure steam. By comparison, geothermal steam supplied to the turbines contains CO_2, H_2S, NH_3 and H_2.

At the Wairakei Power Station the excellent performance of constructional materials compared with the potential for cracking type failures is generally assumed to be due to the conservative approach which was adopted when materials were chosen for plant components. For example the turbine rotors were manufactured from a low strength steel, (yield strength 350-430 MNm^{-2}) and have performed successfully for 20 years.

The same power output can be obtained from smaller turbines rotating at higher speeds using medium strength steel, 550-700 MNm^{-2} yield strength, which would result in significantly lower capital costs. However the cracking resistance of these medium strength steels in geothermal steam has not been reliably established. It is necessary to obtain this information before deciding on a rotor material. The disastrous consequences of a brittle fracture of a rotor or rotor disc is exemplified by the Hinkley Point failure (Kalderon, 1972). This paper describes a program currently being pursued, which uses a fracture mechanics approach to cracking resistance, and reviews the literature relevant to this problem.

SULPHIDE STRESS CRACKING

Brittle failure of steels in environments containing hydrogen sulphide, known as sulphide stress cracking is a phenomenon encountered in the oil industry as well as in geothermal power production. It is well established (Treseder, 1973) that sulphide stress cracking is a form of hydrogen embrittlement where the source of the hydrogen is the corrosion reaction of the steel with aqueous sulphides. McAdam et al, 1980 have established that corrosion in geothermal environments (Broadlands BR22) is accompanied by the entry of atomic hydrogen into the steel. These results are similar to those found by Foster, 1962 for Wairakei fluids. The hydrogen sulphide promotes the entry of hydrogen into the steel, (Zakcroczymski et al, 1976).

The use of steels in sulphide containing environments in the oil industry is covered by a NACE standard MR-01-75, which recommends a maximum hardness of $22R_C$, equivalent to an ultimate tensile strength of ~770 MNm^{-2}, which is supported by a large amount of experimental evidence (Treseder, 1973) showing that cracking susceptibility increases with hardness (Heady, 1977) and yield strength (Dvoracek 1970). The above results were obtained at ambient temperatures where cracking susceptibility is a maximum; at higher temperatures cracking susceptibility decreases markedly. As measured by time to failure, (Townsend, 1972), susceptibility decreased by a factor of 200 between T = 30°C and 80°C. Marshall and Tombs, 1968, observed a similar trend when testing geothermal bore casing steels using constant-load, notched tensile specimens. No failures occurred in 80 days exposure to geothermal steam at T = 190°C with specimens loaded to 90% of their notch strength, while all steels tested failed in cold geothermal condensate at T = 30°C, some at very low fractions of their notch strengths. Thus sulphide stress cracking exhibits the typical characteristics of hydrogen delayed fracture with the special peculiarity that the amount of hydrogen entering the steel is controlled by the rate of the corrosion reaction. The fracture toughness will depend on strength level, microstructure and temperature.

STRESS CORROSION CRACKING

Kalderon, 1972 has described the investigation of the catastrophic failure of a steam turbine which occurred at the Hinkley Point A Station in 1969. The cause of the failure was stress corrosion, cracks initiating at key ways machined in the shrunk-on turbine-disc bores. In subsequent examination of turbine discs and rotors at other stations, a high proportion were found to have cracks. The disc material was a low alloy steel (0.3%C, 3% Cr, 0.5% Mo) having an ultimate tensile strength in the range 850-1000 MNm^{-2}. It was suggested that in wet steam, stagnant conditions were created in the key ways, causing corrosion pitting and stress corrosion crack growth from these pits. Initially it was postulated (Gray, 1969) that impurities in the steam had contributed to the cracking, probably by evaporative concentration in the unwashed key ways, because stress corrosion cracking of low alloy steels was known to occur in hot concentrated solutions of hydroxides, carbonates, phosphates, etc., (Carter and Hyatt 1973). However exhaustive analysis of boiler steam did not show any unexpected impurities.

Subsequently both Parker, 1978 and Roberts and Greenfield, 1979 tested a range of low alloy steels of the same composition as the failed disc and also the 3½ NiCrMoV type having ultimate tensile strengths in the range 700-1000 MNm^{-2}. They showed that in pure wet steam at T = 90°C, cracks grew in pre-cracked specimens at slow rates, which are nevertheless significant in plants expected to last for twenty years or more; growth rates were in the range 0.6mm to 12mm per year, increasing with strength level. The initiation time for cracks was very long and only occurred at very high levels of stress; (no cracking at 50% of proof stress but cracking at 110% of proof stress). As the strength level of the steel was raised the initiation times decreased, perhaps because the critical pit depth for the onset of sub-critical cracking was smaller at higher stresses.

The results found by Roberts and Greenfield, 1979 have implications for rotor design and material selection for use in geothermal steam. Braithwaite and Lichti, 1980 observed pitting corrosion on AISI 4140 low alloy steel in simulated turbine conditions at Broadlands BR22 corrosion test rig, i.e: separated steam T = 160°C, P = 650kPa, wet steam, T = 105°C, P = 126kPa, and aerated wet steam, with the greatest intensity of pitting occurring in the last environment. It is possible that the pitting which occurred in the nominally non-aerated environments was caused by the air which entered the test chambers on opening the rig for sample changes. Nevertheless there is a high probability that pitting will occur in geothermal steam turbines and therefore a high probability that crack initiation sites will exist, apart from those which may be introduced during manufacturing such as residual tensile stresses. Consequently to resist crack growth the turbine rotor steel must have a high degree of toughness. The best method for identifying the most appropriate steel is the fracture toughness test using fracture mechanics concepts.

FRACTURE TOUGHNESS TESTING

Linear elastic fracture mechanics was first developed for determining the conditions which allow the initiation of a fast running brittle fracture, a purely mechanical process which occurs in high strength steels, and its application to this type of process has been reviewed by Irwin and Wells, 1965. Fracture mechanics characterizes the fracture toughness of a steel in terms of a single variable, the plane strain stress intensity K_I, which is proportional to the product of the nominal stress and the square root of the flaw size. Above a critical stress intensity, K_{Ic}, fast brittle fracture will occur. Values of K_I for various types of loadings and crack geometries have been calculated (see for example, Paris and Sih, 1969) which allow the results of laboratory tests, (ASTM E399-78a) to be used for predicting the response of larger structures to various stress conditions. Consequently fracture toughness testing using a fracture mechanics approach yields the combination of design stress and flaw size that would be required to cause sudden failure in a large structure.

More recently fracture mechanics concepts have been applied to the phenomenon of environmentally reduced fracture toughness. Slow crack growth (often described as sub-critical cracking) may occur over a long period of time, (as happened in the Hinkley turbine-disc failure), by a hydrogen embrittlement or stress corrosion cracking mechanism, at stress intensities below K_{Ic}. Finally at a critical flaw size, K_{Ic} is exceeded and rapid failure occurs. The application of fracture mechanics to stress corrosion cracking has been reviewed by Brown, 1966, who first introduced the concept of a threshold stress intensity K_{Iscc}, for a particular material and an environment, below which cracks will not propagate. Oriani 1974 has presented strong evidence supporting the concept of a threshold stress intensity required to cause crack propagation assisted by hydrogen. He established a relationship between K_{Iscc} and the pressure of hydrogen required to cause crack propagation in AISI 4340 of 1724 MNm^{-2} (250ksi) yield strength.

When tested in air, medium and low strength steels usually have sufficient fracture toughness so that general yielding will occur before the onset of brittle fracture, thus preventing the measurement of K_{Ic} using normal sized specimens, i.e. of thickness equal to 2.5cm. The substantial reduction in fracture toughness to a level where fracture mechanics concepts can be applied is due to the influence of the environment.

CRACK INITIATION

Fracture mechanics does not deal with the initiation of environmentally-assisted cracking. On the contrary, the presumption is that flaws exist at which cracks will initiate in an engineering structure, but that the size of these flaws can be controlled during fabrication or at least detected during inspection. The test specimen is usually pre-cracked.

This philosophy is appropriate for materials testing in geothermal environments where the possibility of pitting and therefore of crack initiation is greater than in pure steam. The steel selected must have sufficient toughness so that the design stress-flaw size combination is below the threshold stress intensity, K_{Iscc} for the corrosive environment, where the margin of safety is in terms of allowable flaw size. If pitting occurs during operation, there is an admissable flaw size which governs the conditions for safe operation, rotor reconditioning or renewal.

power station. The corrosion test rig at Broadlands BR22 has been described by Braithwaite and Lichti, 1980.

The physical conditions of the test environments which are designed to simulate turbine conditions are listed in table 1. The partial pressure of the gases present in the steam phase are shown in table 2. Data are not yet available for the wet sub-atmospheric steam environment which represents turbine exhaust conditions.

The composition and mechanical properties of the rotor steel used in the Wairakei B Station is shown in table 3, which also contains the same data for a low alloy steel heat-treated to three different conditions, selected for the test program. The steel composition is almost identical to that used for the Wairakei B Station, and a full anneal at T = 850°C gives a steel with almost the same mechanical properties. The steel heat-treated by oil quenching and tempering at T = 650°C has a Vickers hardness of 240, which corresponds

TABLE 1. TEST CONDITIONS AT BROADLANDS CORROSION RIG - BR22

Test environment	Pressure kPa	Temperature °C	Mass Flow kg/hr	Fluid Velocity dm/min	Comments
Bore fluid	650	160	178	14.5	2 Phase Fluid
Separated High Pressure Steam	650	160	40	11.6	Dry Steam
Wet Low Pressure Steam	126	105	57	215.6	Wetness content 10%by weight
Wet Low Pressure Aerated Steam	135	106	32	129.9	Wetness content 10%by weight 3% of air added
Wet Sub-atmospheric Steam	17	55	-	-	Wetness content 10%by weight
Condensate	300	Cold	14	.012	Liquid

TABLE 2. CHEMICAL CONDITIONS OF TEST ENVIRONMENTS**
GAS PHASE PARTIAL PRESSURES /Pa

Environment	CO_2	H_2S	NH_3	H_2	CH_4	N_2	O_2
Bore fluid	6500	133	25.4	6.1	82	40.7	0.4*
H.P. steam	5530	123	26.9	5.23	67.9	51.7	2.3*
Wet L.P. steam	1070	21	4.61	0.85	11.4	11.8	0.88*
Wet L.P. steam Aerated	1500	26	6.2	1.5	11	$10.9x10^3$	$3x10^3$
Wet steam Sub-atmospheric			-			-	.
Condensate	$286x10^3$	$4.36x10^3$	$5.9x10^{-5}$	290	$3.8x10^3$	2.9x103	-

* Possibly sampling contamination ** Glover, 1980

TEST PROGRAM

The concepts described above have been used in a program to select a steel for use as a turbine rotor in the proposed Broadlands-Ohaki Geothermal

approximately to the maximum hardness recommended by the NACE standard M-01-75. The mechanical properties of the steel resulting from oil quenching and tempering at T = 595°C are approximately equivalent to those found for the rotor

TABLE 3. COMPOSITION AND MECHANICAL PROPERTIES OF THE TURBINE-ROTOR

	Composition %								Mechanical Properties				
	C	Mn	Si	S	P	Ni	Cr	Mo	0.2% Yield Strength MNm^{-2}	Tensile Strength MNm^{-2}	Hardness Vickers	Elongation %	Reduction in Area %
Wairakei B Station Rotor	0.4	0.8	0.3	0.04	0.02	1.10	0.35	0.05	350-430	615-745		21-29	43-56
Test Steel A Fully Annealed at T = 850°C	0.4	0.8	0.2	*0.02	*0.02	1.04	0.57	0.12	490	760	210-212	23	58
Test Steel B Oil Quench from 850°C Temper 650°C					"				758*	840*	240-245		
Test Steel C Oil Quench from 850°C Temper 595°C									880*	1007*	295-300		

* Manufacturers Data

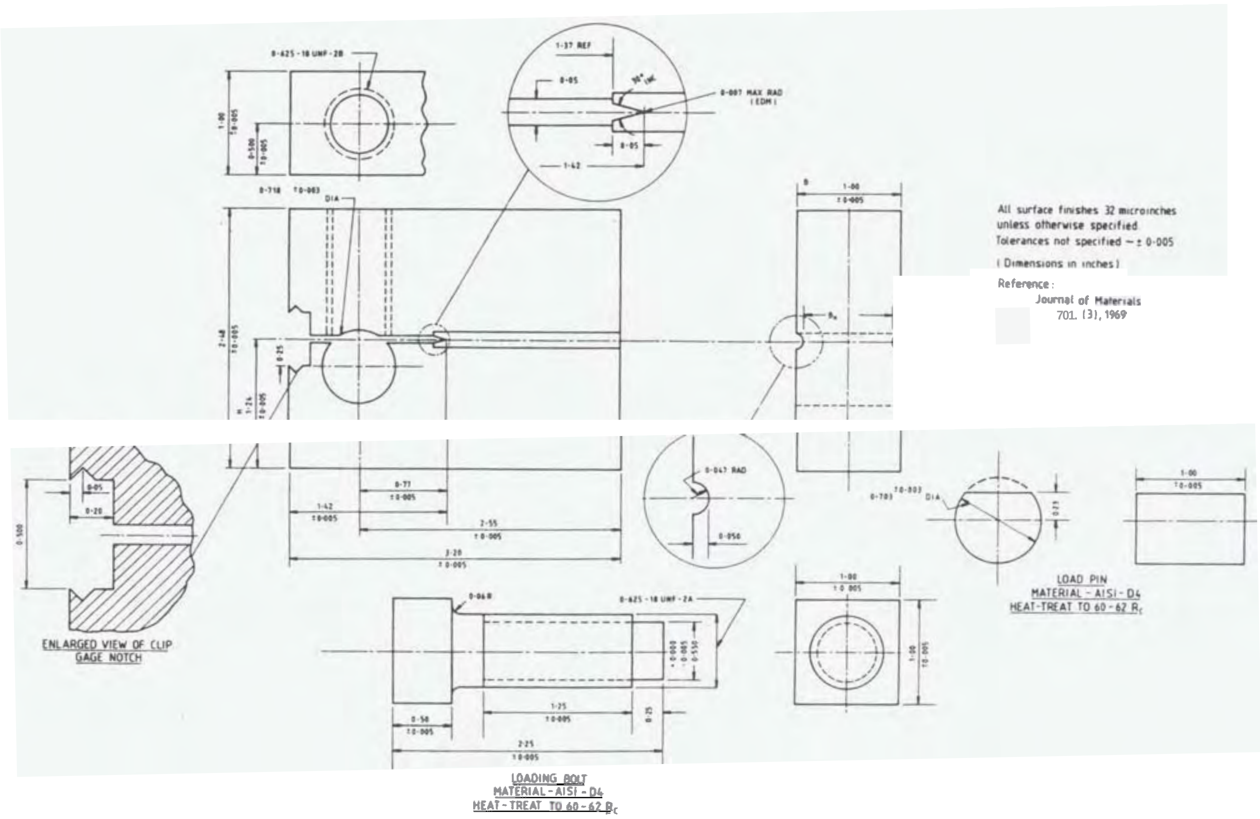

FIG. 1. MODIFIED WEDGE-OPENING-LOAD SPECIMEN FOR K_{Iscc} ENVIRONMENTAL FRACTURE TOUGHNESS TESTING

steels used in pure steam; that is similar to the steels used by Roberts and Greenfield, 1979.

Fracture toughness measurements are in progress using a self-stressed wedge-opening-load test specimen. The design, Fig 1, follows Novak and Rolfe, 1969. The stress intensity at the crack tip for this specimen is given by equation 1, where.

$$K_I = \frac{PC_3(\frac{a}{w})}{B\ (a)^{\frac{1}{2}}} \qquad \ldots\ (1)$$

P = load
a = crack length
w = specimen depth
B = specimen thickness
C_3 = function of a/w given by Novak and Rolfe, 1969.

The advantages of this test specimen design are its portability and the fact that it is self stressed thus eliminating the need for large testing fixtures or test machines, both of which are particularly difficult to arrange for field tests in geothermal steam. It has been used successfully by Parker, 1978 and Roberts and Greenfield, 1979 for measuring slow crack growth in pure steam and by Oriani and Josephic, 1974 for determining the threshold stress intensity for crack growth in pure hydrogen atmospheres. An interesting question which may be answered by these experiments is whether the gases present in the steam, H_2S, C02 and NH3 accelerate or retard crack growth rates compared with that found for pure steam by Parker, 1978 and Roberts and Greenfield, 1979.

Oriani, 1978 has suggested that the equivalent hydrogen fugacity of the dissolved atomic-hydrogen in the steel is a convenient parameter for comparing hydrogen embrittlement phenomena occurring in different hydrogen charging environments, for example different H_2S concentrations, or electrolytic hydrogen charging. This suggestion has been followed by measuring the hydrogen permeability in the test steels exposed to the various environments, table 2, from which the equivalent hydrogen fugacity of the dissolved hydrogen may be calculated. The technique is similar to that used by Foster, 1962.

CONCLUSIONS

Steels exposed to geothermal steam are likely to suffer environmentally-assisted cracking. At temperatures less than T = 100°C the dominant mechanism is probably hydrogen assisted cracking whereas above this temperature, stress corrosion cracking characterized by very slow crack growth rates may occur. Crack initiation is unlikely to be a difficult process because of the high probability of pitting corrosion.

Consequently a fracture mechanics approach to determine fracture toughness is required for selecting a steel for a turbine rotor to be used in geothermal steam.

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