Nondestructive Evaluation of a Turbine Generator Casing

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ABSTRACT

Background on the electric potential crack sizing approach will be presented along with experimental evaluations of the accuracy of the technique. Basic material properties required for a fracture mechanics evaluation are also presented. These properties, coupled with an appropriate numerical stress analysis of the component and a knowledge of the flaw size from nondestructive testing, enable estimates of the remaining useful life of the component. An example of such a residual life estimate is presented.

KEWORDS

NDE; ACPD; cracks; 2 1/4 Cr - 1 Mo steel; fitness for service

INTRODUCTION

The ability to measure the depth of surface breaking flaws in a component is a primary issue that the nondestructive evaluation and the fracture communities must address. An accurate measure of the flaw depth is necessary to determine the stress intensity associated with the flaw. The stress intensity provides the driving force for flaw growth and a driving force analysis is required to ascertain the fitness for service of the component. Thus, without an accurate measure of the flaw depth, fitness for service decisions to replace, repair, or accept various components are no better than engineering judgment.

The practice of replacing all components with linear, surface breaking discontinuities is overly restrictive and costly. Repairing all linear, surface breaking discontinuities is overly restrictive, costly, and may be more detrimental to the life of the component than allowing the discontinuity to remain. Accepting all linear, surface breaking discontinuities is unacceptable when compared to current acceptance criteria and under certain circumstances will decrease the service life of the component.

The ability to measure the depth of a discontinuity, coupled with the determination of a critical flaw size and crack growth rates will provide a quantitative method to determine when a repair is necessary and what action is warranted.

The purpose of this investigation was to evaluate the effectiveness of an electric potential technique in sizing surface breaking flaws in steam turbine components. The flaws examined in this investigation were located in the casing of a Ship Service Turbine Generator (SSTG). These components undergo thermal stress cycles during the course of normal operation. The thermal stress cycling is responsible for the formation of cracks at geometric discontinuities in the component. The region of the component where this is a principle concern is the floor-to-wall radius of the steam entryway which is shown in Fig 1.

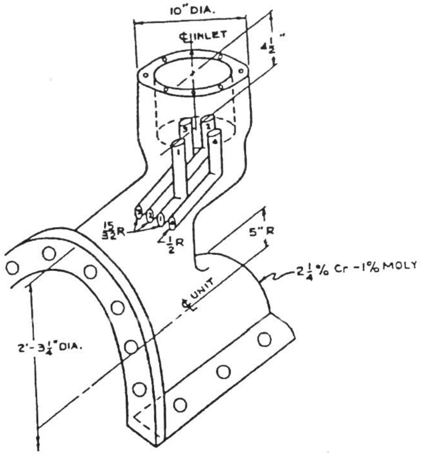

Fig. 1. Upper casing of Ship Service Turbine Generator

ELECTRIC POTENTIAL TECHNIQUES IN NDE

The electric current test method has been reported to have the ability to estimate discontinuity depths. The electric current method uses the perturbation of the electric field caused by the discontinuity. The potential that is associated with the current flow in the material is correspondingly changed with the introduction of a discontinuity. It is this change in the potential that is measured and related to the discontinuity depth.

Various methods have been used to inject the electric field and measure the potential change associated with a discontinuity. Thornton (1942) and Jackson (1948) used four electrodes, two introducing current and two measuring potential. These investigators used the direct current technique with unequal spacing between the electrodes. Hirst (1947) also used the direct current technique to measure the potential while introducing the current at a position remote from the discontinuity, thereby producing a uniform current distribution. Armour (1948) also using the direct current method, employed a four electrode, equally spaced array to detect but not to measure, discontinuities. Buchanon and Thurston (1956) extend the use of the probe array developed by Armour to provide estimates of crack depth.

More recently, the alternating current potential drop (ACPD) technique has been employed for measuring depths of surface breaking discontinuities. This technique relies on the principle that, due to the skin effect, alternating current is carried in a thin layer at the surface of the material under test. The depth of this current carrying layer is controlled by the frequency of the alternating current. Therefore, for a given frequency, the potential drop between any two points in the AC field is proportional to the bulk resistivity of the material and the path length between the two contacts. The presence of a surface breaking discontinuity within this AC field represents an increase in the resistance to the AC flow by causing an increase in the surface path length. This phenomenon allows potential drop measurements in the vicinity of the discontinuity to be directly related to the discontinuity depth.

Deutsch and Vogt (1978) used a three pole probe with a fourth, detachable pole to measure depth with the ACPD technique. They concluded that measurement error was within 10% of the actual crack depth and that the ACPD technique was more accurate in complex geometrical components than the DC technique. Dalberg (1981) was able to measure depths of laboratory fatigue cracks to an accuracy of +/- 0.5mm. He suggested that the accuracy would decrease for sizing real cracks. Duncumb and Mudge (1982) used the ACPD technique to measure depths of discontinuities at the toes of welds. Their results indicated the tendency of the technique to over-estimate the depth of very shallow cracks and to under-estimate the deeper cracks.

MATERIALS

The material examined for this investigation was a cast 2-1/4Cr - 1Mo steel with a chemistry consistent with the requirements of ASTM A217 Grade WC-9. Mechanical test specimens were removed from the casing of an SSTG that had experienced extensive service. The testing included tensile tests in accordance with ASTM E8, Charpy V-notch tests (ASTM E23), fracture toughness tests (ASTM E813), and fatigue crack growth rate tests (ASTM E647). Results of these tests are presented in Tables 1 and 2 and in Fig. 2 and 3. The room temperature tensile properties of the steel were found to be consistent with previously published data on the same grade of steel (Logsdon 1972). Charpy impact toughness performance of the casing steel exhibited a similar transition temperature behavior but a reduced upper shelf in comparison with previously published data (Logsdon 1972). The room temperature fatigue crack growth performance of the casing steel was also consistent with previously published data (Logsdon). Coefficients for the Paris law growth rate equation were C = 5.82×10^{-11} and n = 3.61. The equivalent linear elastic fracture toughness of the steel ranged from 125 ksi$\sqrt{\text{in}}$ at room temperature to 89 ksi$\sqrt{\text{in}}$ at 550 F. These results indicate that the fracture toughness of the SSTG casing tested above room temperature was generally lower than the values reported by Logsdon (1972) which were tested at sub-zero temperatures.

Table 1. Mechanical properties at 70°F

IDENTIFICATION	ULTIMATE STRENGTH (ksi)	0.2% OFFSET YIELD STRENGTH (ksi)	ELONGATION IN 2 INCHES (%)	REDUCTION OF AREA (%)
SSTG CASING 2-1/4Cr - 1Mo CAST	85.9	57.4	18.6	40.3
(Logsdon, 1972) 2-1/4Cr - 1Mo CAST	84.0	60.0	15.0	32.0
ASTM A217	70 - 95	40 (min)	20	35

TABLE 2 - RESULTS OF FRACTURE TOUGHNESS TESTS

MATERIAL	IDENTIFICATION	THICKNESS (inches)	TEMPERATURE (°F)	J1c (E813) (in-lbs/sq in)	EQUIVALENT K* (ksi-$\sqrt{in}$)	Kq (E399) (ksi$\sqrt{in}$)
SSTG CASING	GFB-71	1.0	70	536	125	55
2-1/4Cr - 1Mo	GFB-72	1.0	70	455	115	60
CAST	GFB-74	1.0	300	394	107	50
	GFB-73	1.0	500	275	89	49
(Logsdon, 1972)	#12	2.0	-320	---	---	27
2-1/4Cr - 1Mo	#18	2.0	-50	---	---	97
CAST	#15	4.0	-150	---	---	60
	#13	4.0	-100	---	---	133

* - K = (J x E)^1/2

The tensile and Charpy results are used primarily to establish the basic mechanical characteristics of the steel in comparison with specification requirements or with other steels. The fracture toughness and fatigue crack growth rate data, taken together, comprise the material's resistance to crack growth.

EXPERIMENTAL

The ACPD instrument used in this investigation has a single control and a digital read-out of the potential measurement. Current input is via fixed pins in the four pin probe. The instrument operates at a frequency of 1 kHz which results in a skin depth in steel of 0.017 inches. Voltage drop measurements are via spring-loaded pins equally spaced between the current input pins. Adequate field current as well as potential sensing contact is indicated by green lights on the instrument front panel. The pin spacing is 0.1 or 0.2 inches depending on the probe selected. The potential drop across the probe pins is amplified and presented by the LED display. The instrument weighs approximately 5 pounds and is 3.5 inches high by 8.5 inches wide by 9 inches deep and thus is easily portable.

The principle of operation for potential drop measurements is to make a first measurement with one of the current injection pins spanning the discontinuity (the reference potential measurement) and a second measurement with one current injection pin and one potential measuring pin straddling the discontinuity. These measurements are then used in the equation from Michael et al. (1982) to determine depth:

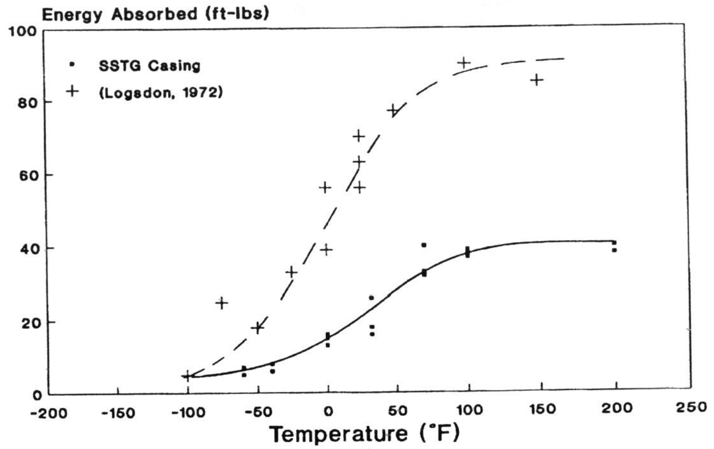

Fig. 2. Results of Charpy V-notch tests.

$$d = [(V_{on}/V_{off}) - 1]\ (s/2) \qquad (1)$$

where: d is the depth of the discontinuity, V_{on} is the voltage measurement across the discontinuity, V_{off} is the voltage measurement adjacent to the discontinuity, and s is the spacing between the voltage measuring pins.

A calibration block (14 in. x 2 in. x 1 in.) with a series of notches 0.010 inches wide and depths of 0.015, 0.030, 0.060, 0.100, 0.200, ..., 1.0 inches was used to demonstrate the accuracy of the instrument. The results of the calibration tests are presented in Fig. 4. Regression analysis indicates that a binomial equation best fits the data. The equation for the curve is:

$$y = 1.9x^2 + 1.2x + 0.00005 \qquad (2)$$

where: y is the depth as corrected by the best fit curve, and x is the depth predicted depth from ACPD.

The coefficient of determination is 0.996, that is, 99.6% of the total variation is explained by the curve.

The depth of a crack along the wall-to-floor radius of a SSTG casing was predicted using the ACPD technique and then verified through metallographic examination. The results of the predicted depths compared to the actual depths are presented in Table 3.

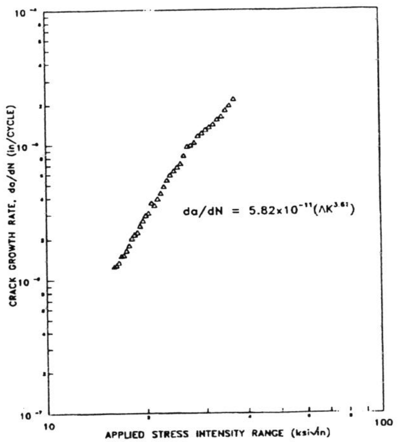

Fig. 3. Fatigue crack growth rate 2-1/4Cr - 1Mo cast steel.

Application of the empirical fit developed for the EDM flaws applied to the fatigue cracks found in the component leads to a slight underestimation of the actual crack depths. These results indicate a good comparison between the predicted and measured depths.

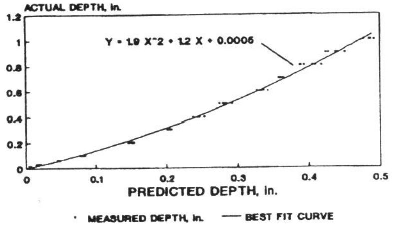

Fig. 4. AC potential drop predicted depths and regression equation.

The instrument was then used to predict the depth of a 360° linear indication at the transition between the wall and floor of a steam casing from a second SSTG. The depths at each measurement point are presented in Table 4. The depth of the crack ranged from 0.03 inches to 0.25 inches. The majority of the depths measured approximately 1/16-inches.

Table 3. Predicted and actual depths of SSTG casing

PREDICTED DEPTH (inch)	CORRECTED PREDICTED DEPTH (inch)	ACTUAL DEPTH (inch)
0.11	0.16	0.19
0.15	0.22	0.23
0.09	0.12	0.17
0.11	0.15	0.16
0.11	0.15	0.14
0.11	0.16	0.17
0.11	0.15	0.17
0.12	0.16	0.16

Table 4. Predicted depths of cracks in a steam casing.

IDENTIFICATION	PREDICTED DEPTH (inch)
A	0.10
B	0.03
C	0.05
D	0.19
E	0.04
F	0.05
G	0.05
H	0.07
I	0.03

DISCUSSION

The resistance of the material to fracture and fatigue crack growth, as previously described, coupled with a numerical stress analysis, enables estimates of the remaining useful life of the component. Such an analysis for an SSTG was conducted by Hulina et al. (1986) and the result is shown in Fig. 5. Shown in this figure is a plot of the remaining cyclic life for a crack at the floor-to-wall radius of the steam entryway of the SSTG, as a function of the crack depth. The cyclic life is based on the number of "cold starts" that the SSTG experiences. A "cold start" is defined as bringing the unit on-line to full power in 11 minutes from ambient conditions to a maximum temperature of 1000 F. The cold start cycle has been shown to force the floor-to-wall radius region in the steam entryway to be plastically loaded in compression. Cracking occurs in this region on the cool-down portion of the cycle which leaves the region in residual tension. Grinding to remove the crack in this case only exacerbates the situation, leading to more rapid crack growth. Use of the remaining life curve shown in Fig. 5, as an alternative to grinding or weld repairing, allows safe operation of the component in the presence of a crack whose depth is accurately know. As such, use of an accurate nondestructive inspection technique like the ACPD method described in this investigation, is essential to reliable estimates of the remaining useful life. An estimate of the remaining life of the SSTG component tested would be approximately 800 cycles based on a maximum crack depth of 0.25-inches.

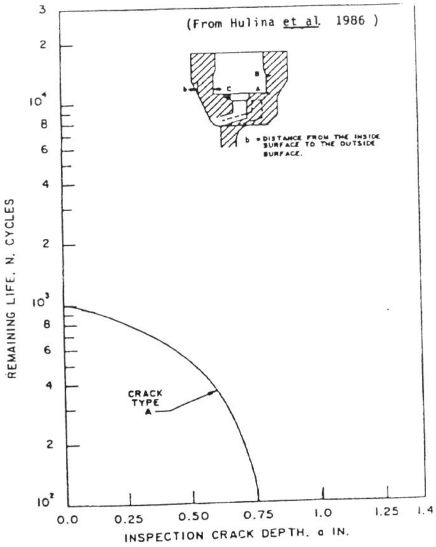

Fig. 5. Remaining life as a function of crack depth for SSTG upper casing.

CONCLUSIONS

The ACPD technique was found to underestimate the depths of both EDM flaws in a test block and actual fatigue cracks in an SSTG. An empirical fit to the EDM data allows for useful estimates of flaw depth from ACPD measurements. Application of this approach to actual fatigue flaws has been shown to provide conservative estimates of flaw depth. Use of the ACPD technique in conjunction with a fracture mechanics analysis provides a quantitative method for determination of the necessity for and/or required frequency of repair work.

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