

THE FATIGUE BEHAVIOUR OF MACROSCOPIC SLAG
INCLUSIONS IN STEAM TURBO-GENERATOR ROTOR STEELS

A. Elsender, R. Gallimore and W. A. Poynton*

INTRODUCTION

A fracture control plan is necessary for any highly stressed component to ensure that catastrophic failure will not ensue from the growth of any natural defects present.

In addition to an accurate knowledge of the components required life, this plan requires information in three main areas:-

- a) an NDT description of the natural defects in the component
- b) initiation and growth behaviour of cracks emanating from the natural defects under the prevailing stress regime and
- c) the maximum size of crack that can be tolerated prior to catastrophic failure.

The objective of this paper is to consider the initiation and growth of fatigue cracks from macroscopic slag inclusions in large steam turbo-generator rotor forgings. The NDT description of defects, and the tolerance of forgings to cracks are the subject of separate investigations.

COMPONENT

Typical rotor forgings for a 500 MW turbo-generator, Figure 1, weigh up to 10^5 kg and operate at up to 3600 rpm. Low temperature rotors (3%NiCrMoV composition) and high temperature rotors (1CrMoV composition) have 0.2% proof strengths of approximately 700 or 600 MPa respectively. During the design life of 30 years, the rotors experience a maximum of 10^4 cycles of stop to start operation.

Ultrasonic inspection prior to final machining classifies defects into two types:-

- a) inclusions that are individually resolvable
- b) clouds of irresolvable inclusions, i.e. numerous inclusions within the beam path.

TEST MATERIAL AND PROGRAMME

Tensile specimens were selected from regions of rotors containing ultrasonic defect 'clouds' and were positioned such that the tensile loading was in the same direction as the hoop stress in the component. The test surfaces of the specimens were then progressively ground to reveal at least one inclusion before being polished to optimise conditions for 'on test' photography and microscopy. Although the defects were ultrasoni-

*Metallurgy Department, Research and Development Laboratories,
C. A. Parsons & Co. Ltd., Newcastle Upon Tyne, UK.

cally irresolvable in the initial inspection, it was subsequently found that the spacings of the defects were sufficient to preclude any fracture mechanics interactions.

Four tests were performed, two on the 31/2NiCrMoV rotor steel and two on 1CrMoV. Each specimen was cycled a minimum of 10^4 times from zero to the maximum design stress for the material. In some tests there was little evidence of surface damage under these conditions, and the stress range and/or number of cycles was therefore increased to promote cracking.

Upon completion of the tests the specimens were broken open at low temperature for examination by scanning electron microscopy, Figure 2. A total of 17 inclusions was examined on the four specimens, Table 1. To assist in fracture mechanics interpretation, the dimensions quoted assumed that the inclusion and fatigue front were ellipsoidal in shape. The chemical composition of the macroscopic slag inclusions was examined by energy dispersive x-ray analysis, and all were shown to be of the aluminosilicate type.

Two aspects of the inclusion behaviour were studied quantitatively:-
a) the conditions governing the initiation of fatigue growth from the inclusion and
b) the rate of fatigue growth from the inclusion.

INITIATION AND PROPAGATION OF FATIGUE GROWTH

Initiation of Growth from Inclusions

For fatigue growth from sharp cracks, the threshold stress intensity, ΔK_0 must be exceeded. Jerram et al [1] indicate threshold values of 7-9 MPa $m^{0.5}$ for material of this type tested in air with a minimum to maximum stress ratio of about 0.1.

Stress intensity ranges calculated for all the inclusions, Table 1, indicate that a similar threshold also applies for initiation from inclusions, Figure 3.

Harkegard [2] found that inclusions in hardened and tempered steels behaved in a similar manner.

Fatigue Propagation from Inclusions

The propagation of fatigue cracks is governed by the Paris and Erdogan [3] relationship

$$\frac{d_a}{d_N} = C_1 (\Delta K)^y \quad (1)$$

where C_1 and y are constants. For rotor steels at room temperature, extensive testing [4] indicates an optimum value of $y = 3$, with $C_1 = 8 \times 10^{-12}$ encompassing all available data and $C_1 = 3 \times 10^{-12}$ representing a mean line through the data. Since

$$\Delta K = C_2 \cdot \Delta \sigma \cdot a^{0.5} \quad (2)$$

where C_2 is the appropriate coefficient for ellipsoidal surface or internal cracks.

Substituting equation (2) into (1) and integrating gives,

$$\left\{ a_o^{-0.5} - a_f^{-0.5} \right\} = C_1 \left\{ \frac{C_2^3 (\Delta \sigma)^3 N}{2} \right\} \quad (3)$$

The terms in parenthesis were plotted, Figure 4, for the inclusions where measurable growth occurred. The two slopes drawn through the data represent the maximum and mean values of the coefficient C_1 defined above. Clearly the fatigue growth from inclusions is identical to that from pre-cracks.

CONCLUSIONS

The initiation and propagation of fatigue cracks from macroscopic aluminosilicate inclusions in 31/2NiCrMoV and 1CrMoV rotor forging materials can be analysed by linear elastic fracture mechanics assuming the shape of the inclusion is similar to an ellipse.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the active collaboration received from the CEGB during the course of this work. They are also grateful to C.A. Parsons & Co. Ltd., for permission to publish the paper.

REFERENCES

1. JERRAM, K. and PRIDDLE, E. K., J. Mech. Eng. Sci., 15, No. 4, 1973, p.271.
2. HARKEGARD, G., Eng. Fract. Mech., 6, December 1974, p.795.
3. PARIS, P. C. and ERDOGAN, F., J. Basic Eng. (Trans ASME Series D), 85, 1963, p.528.
4. LINDLEY, T. C. and RICHARDS, C. E., Central Electricity Research Labs. Report RD/L/R 1804, July 1972.

Table 1 Summary of Fatigue Tests on Rotor Material Containing Inclusions

Material	INCLUSION DESCRIPTION		INCLUSION SIZE		Stress Range (MPa)	ΔK_I (MPa.m ^{0.5})	No of cycles	FINAL DEFECT SIZE		$\left\{ \frac{a_o - 10^{-6} a_f - 10^{-4} z}{2} \right\}$ (in SI units)	$\left\{ \frac{C_2 (20)^3 N}{2} \right\}$
	Inclusion No	Position Surface-Embedded-E	Normalised length (m x 10 ⁻³)	Normalised depth (m x 10 ⁻³)				Normalised length (m x 10 ⁻³)	Normalised depth (m x 10 ⁻³)		
3 1/2 NiCrMoV	1	S	3.75	1.85	8 - 463	25	1x10 ⁴	6.00	3.00	4.99	0.98x10 ¹²
	2	S	3.35	0.77	8 - 463	21	1.3x10 ⁴	3.65	0.90	2.70	5.34x10 ¹²
	3	S	3.00	0.20	8 - 309	8	1x10 ⁴	NO GROWTH	NO GROWTH		
	4	S	3.35	0.20	8 - 386	10	2.5x10 ⁴	NO GROWTH	NO GROWTH		
1CrMoV	5	E	2.00	0.17	8 - 309	8	1x10 ⁴	3.75	0.65	31.49	4.78x10 ¹²
	6	S	2.00	0.28	8 - 386	6	1x10 ⁴	NO GROWTH	NO GROWTH		
	7	E	2.20	0.09	8 - 309	9	1x10 ⁴	3.00	0.28	16.94	3.94x10 ¹²
	8	E	1.87	0.13	8 - 386	5	1x10 ⁴	EXTENSIVE GROWTH ACROSS SPECIMEN THICKNESS	NO GROWTH		
	9	S	2.35	0.22	8 - 309	6	1x10 ⁴	NO GROWTH	NO GROWTH		
	10	S	1.25	0.22	8 - 386	11	6x10 ⁴	2.42	0.45	19.20	10.26x10 ¹²
	11	S	1.80	0.28	8 - 309	8	1x10 ⁴	NO GROWTH	NO GROWTH		
	12	S	2.06	0.65	8 - 386	12	1x10 ⁴	1.93	0.55	16.33	7.99x10 ¹²
	13	S	1.53	0.3	8 - 386	15	6x10 ⁴	2.16	0.90	6.51	4.99x10 ¹²
	14	S	0.70	0.08	8 - 386	12	6x10 ⁴	1.63	0.45	10.59	7.55x10 ¹²
	15	S	1.33	0.17	8 - 386	7	6x10 ⁴	NO GROWTH	NO GROWTH		
	16	S	1.33	0.08	8 - 309	9	1x10 ⁴	1.37	0.27	15.83	9.60x10 ¹²
	17	S	1.67	0.13	8 - 309	7	6x10 ⁴	1.40	0.14	27.3	10.26x10 ¹²
				8 - 386	9	6x10 ⁴	1.75	0.27	26.85	10.85x10 ¹²	

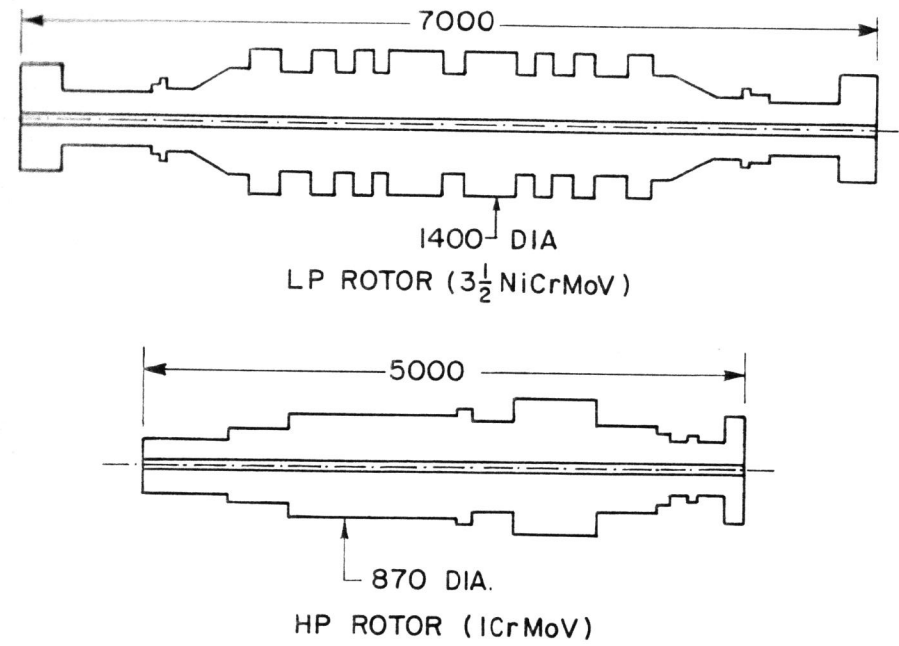


Figure 1 Typical Rotor Forgings for 500 MW Turbo-Generator

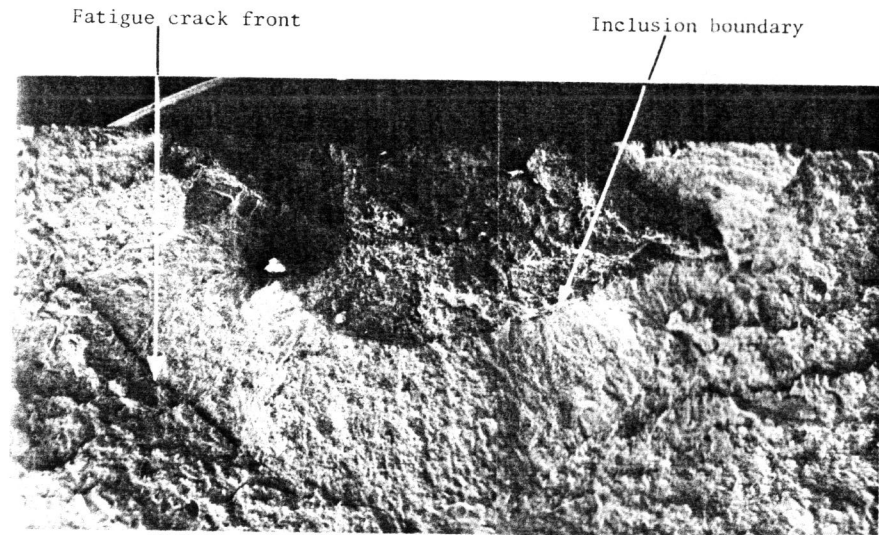


Figure 2 Typical Inclusion and Fatigue Crack Front

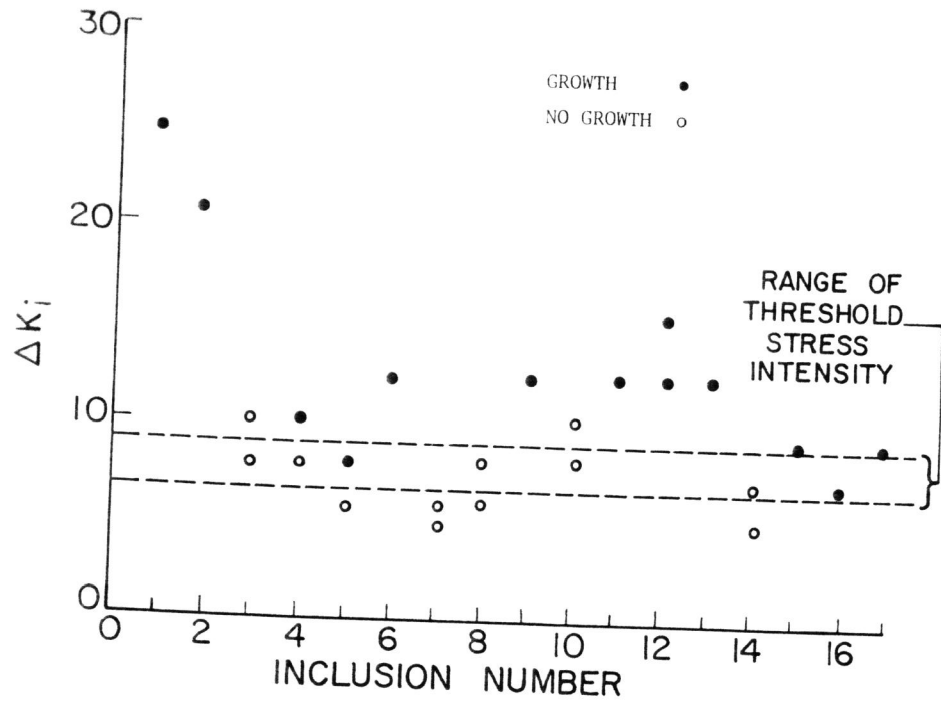


Figure 3 Initiation Behaviour of Defects

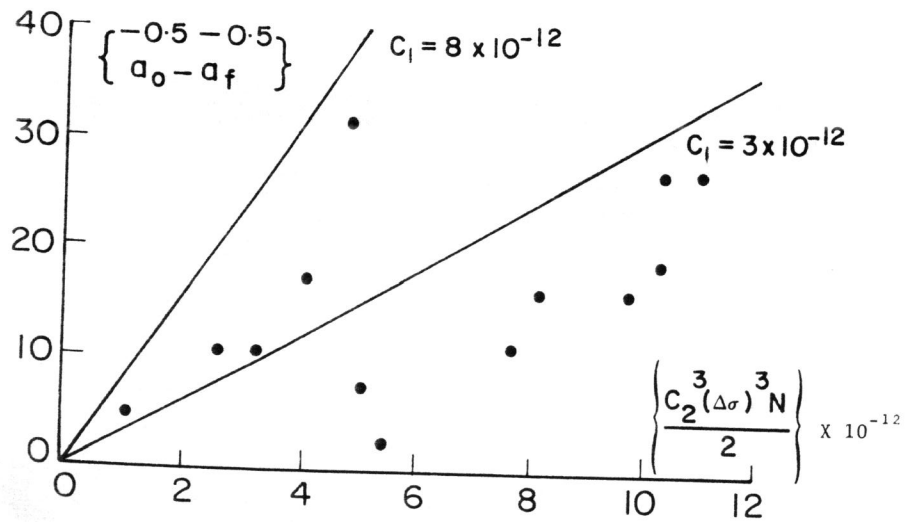


Figure 4 Growth Rate of Fatigue Cracks from Inclusions