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Development of a Test Procedure for the Measurement of Thermal fatigue Resistance of Coatings

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ABSTRACT

Thermal mechanical fatigue (TMF) is an important failure mechanism for coatings used in gas turbine engines. TMF resistance was assessed using a rig designed at NPL in which the sample was directly heated by passage of a large electrical current, and the strain was imposed using a hydraulic actuator. The test was carried out under strain control and heating rates of up to 140 °C per second could be achieved. The temperature strain cycles were controlled using Labview® software. Two cycles have been simulated for industrial and aero use of gas turbines. MCrAlY and Pt diffusion coating systems have been investigated and tested to failure. Metallographic examination of the failed samples yielded information on the fracture process.

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CONTENTS

1 INTRODUCTION 1

2 MATERIALS 2

3 EXPERIMENTAL 2

4 RESULTS 6

5 SUMMARY AND CONCLUSIONS 9

6 ACKNOWLEDGEMENTS 10

7 REFERENCES..... 10

September 2001

INTRODUCTION

Coatings designed for use in the hot section of a gas turbine are required to withstand high temperatures and mechanical stressing. A coating is used for either corrosion or thermal resistance, and will be effective only if it remains intact. Thus the mechanical properties of the coating can have a marked effect on the performance of the system, and data is required to provide designers with assurance that the coating system will be fit for purpose. Additionally, during service ageing effects occur due to oxidation and interdiffusion that will alter the coating properties from the as-produced values. It is important, therefore, to be able to measure the properties of the coating in the aged state and this may involve testing small samples taken from a blade that is to be refurbished.

The fracture strain that a coating can tolerate clearly changes as a function of temperature. Brittle behaviour is observed at low temperatures, and, as the temperature is increased, the material becomes increasingly ductile, and in some materials the transition is relatively well defined so that a ductile brittle transition temperature (DBTT) can be defined. In practice, the information needed by the designer should define conditions under which a coating will crack when subjected to the anticipated service stresses. The DBTT also comes into play when considering thermal mechanical fatigue (TMF) resistance. In this case due to temperature gradients along the length of a blade a hot spot in the centre is found. The material at this point is constrained from expanding by the cooler material surrounding it, and thus is compressively stressed. At high temperatures creep can relieve this stress because the coating creep resistance is generally lower than that of the substrate. On cooling, depending on the extent of the creep relaxation, and differences in thermal expansion coefficients, the coating can be placed in tension, and will crack if the DBTT for a given strain is reached (Figure 1).

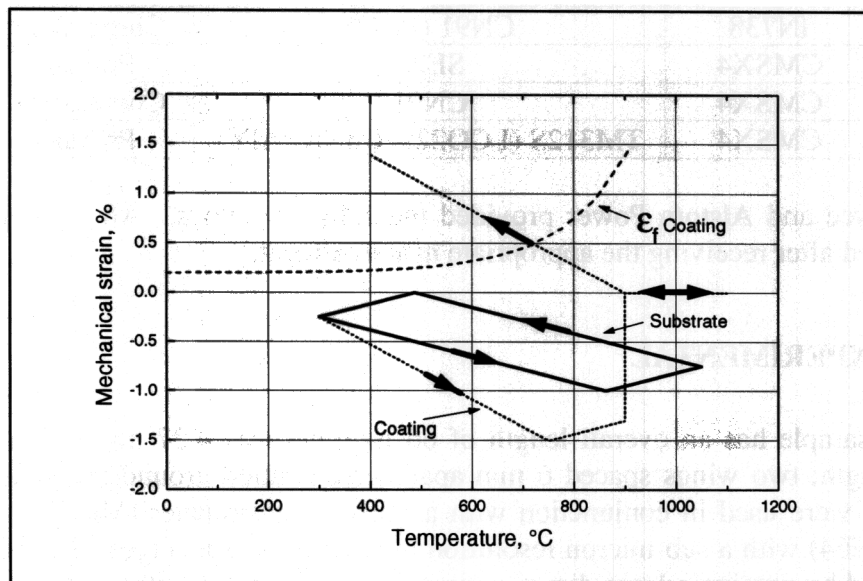


Figure 1 Schematic TMF cycle of a coated component showing the effect of creep relaxation during heating and subsequent tensile cracking on cooling

September 2001

TMF resistance is usually assessed in complex rigs involving closed loop servo controlled hydraulic testing machines with induction heating [1]. Problems with many test procedures are temperature measurement and the ability to control cycle shape. Often thermocouples are welded directly to the sample and there is concern that this could initiate cracking, some workers have used spot focussed radiation pyrometers to overcome this difficulty. The size of normal TMF samples is one of the major constraints in imposing realistic cycles. Working with thin-walled samples overcomes some of these problems, but others are created particularly when working with coatings.

The approach adopted at NPL was to use relatively small samples so that realistic heating and cooling rates could be achieved. In an earlier design of a novel rig for TMF resistance measurement [2] the samples were only 10 x 2 x 2 mm. It was believed that such small samples would be inappropriate for coatings where the edge effect would dominate behaviour. A new rig was designed in which sample size was increased, but which nevertheless would allow realistic heating and cooling rates to be imposed and thus permit a good simulation of service conditions.

2 MATERIALS

Coatings were deposited on IN738 and CMSX4 substrates. Work was carried out on MCrAlY and Pt-aluminised variants supplied by Siemens, Chromalloy UK and Praxair. Table I lists the coating systems investigated in this work.

Table I: Coating systems studied

<i>Substrate</i>	<i>Coating</i>	<i>Supplier</i>
IN738	SE20 (NiCrAlYTaSi)	Praxair
IN738	CN91 (Pt Al)	Chromalloy
CMSX4	SE20	Praxair
CMSX4	CN91	Chromalloy
CMSX4	TM312S (LCO22 – CoNiCrAlY)	Praxair

Rolls Royce and Alstom Power provided the substrate alloys. All coating systems were tested after receiving the appropriate heat treatment.

3 EXPERIMENTAL

The test sample has an overall length of 66 mm and was 4.37 mm diameter in the gauge length; two wings spaced 6 mm apart were centred around the gauge length, and these were used in conjunction with a video extensometer (Messphysik GmbH model ME64) with a sub micron resolution to measure strain (Figure 2). The sample was heated by passing a large direct current of up to 800 A; at 400 A the heating rate was 140 °C s⁻¹, which is comparable with that achieved during normal gas turbine operation. Cooling rates of 25 °C s⁻¹ were possible under ambient conditions. The load was applied using a hydraulic system with a maximum load of 20 kN. Figure 3

September 2001

is a photograph of the test rig, and Figure 4 is a close-up of the sample mounting arrangements.

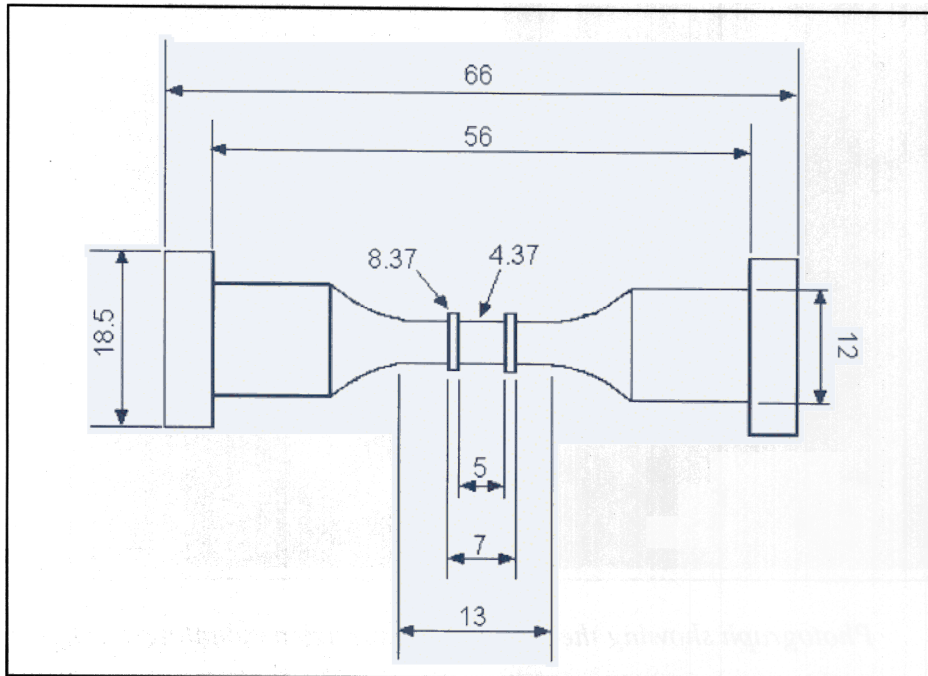


Figure 2 Schematic diagram of the TMF test sample – all dimensions in mm.

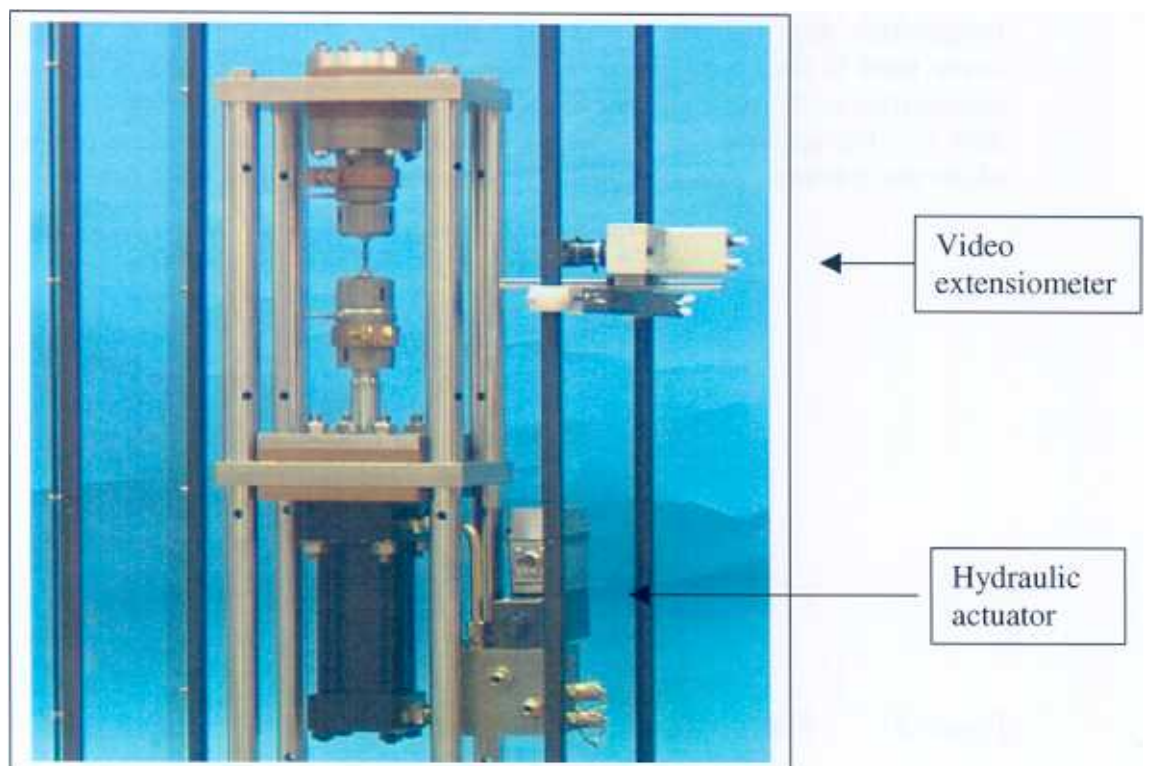


Figure 3 Photograph of the TMF rig showing hydraulic actuator and video extensometer

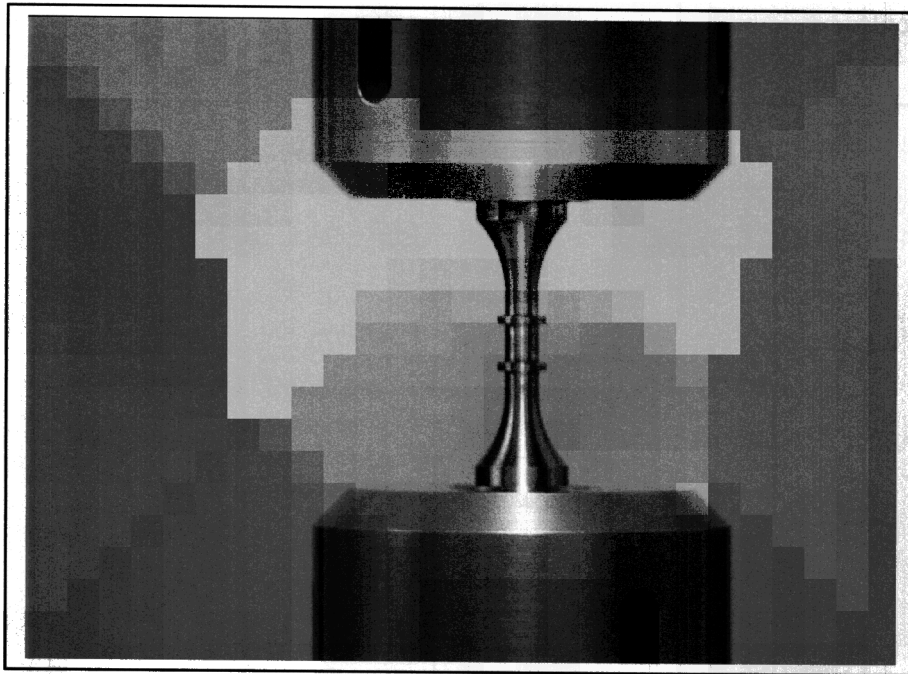


Figure 4 *Photograph showing the detail of the specimen mounting arrangements*

The temperature of the sample was controlled by a thermocouple welded on to one of the wings. An appropriate offset was applied to the control system to account for the temperature drop between the centre and wings of the sample, and the calibration curve used is shown in Figure 5. Thus for the conditions used in this work for a temperature at the centre of the gauge length to be 1000 °C the wing was controlled to 880 °C. The specimen and associated loading train was housed in a polymer box to allow the system to be purged with argon to reduce oxidation during the tests.

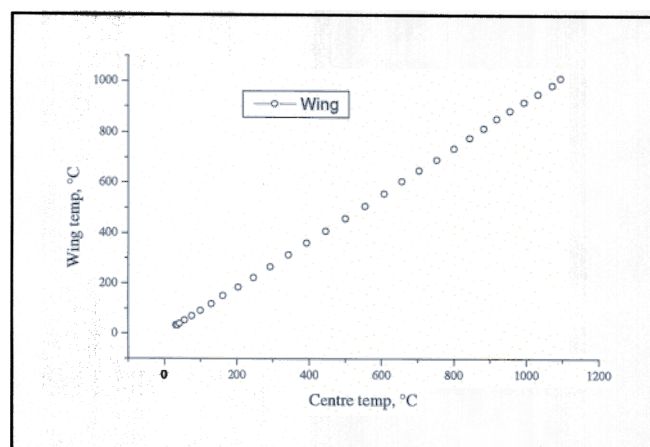


Figure 5 *Temperature calibration curve*

The strain temperature cycles were controlled using bespoke software based on LABVIEW®. The procedure involved first assessing the thermal strain imposed during the test by heating the sample under zero loading and monitoring the strain.

September 2001

This information was then the baseline against which the mechanical strain was imposed. The programming logic used in LABVIEW® is shown schematically in Figure 6.

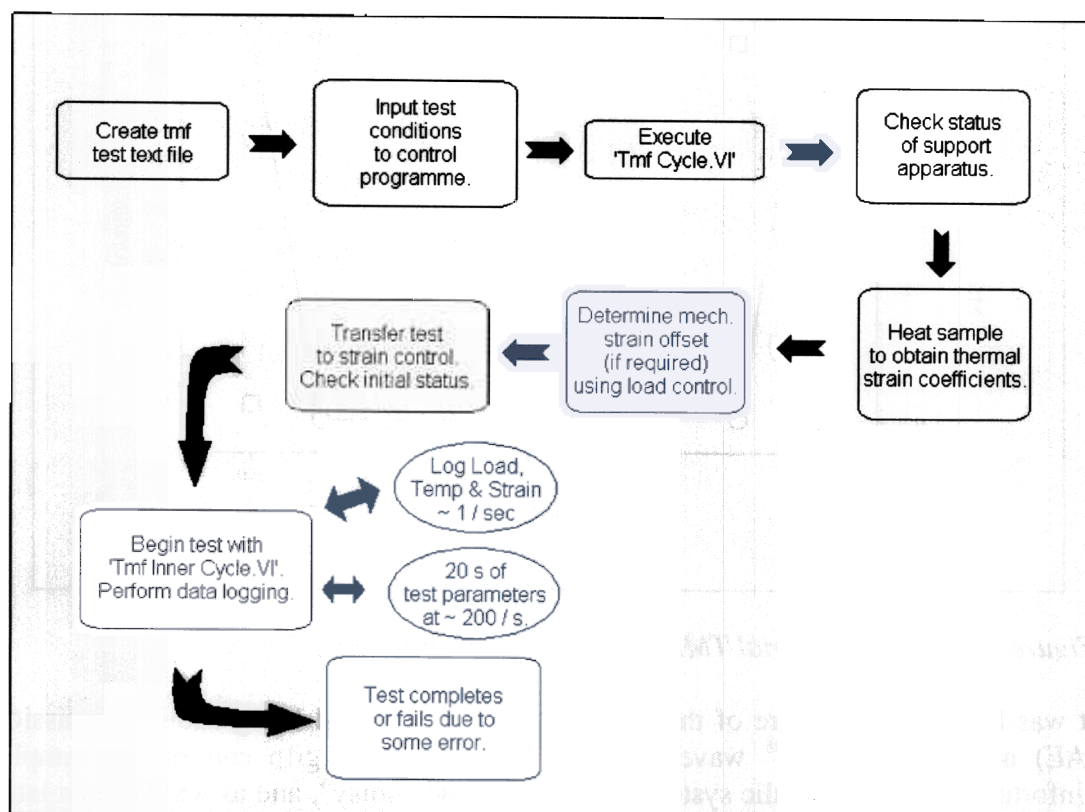


Figure 6 Schematic of the LABVIEW® TMF control program

The cycle was based on an industrial gas turbine and is illustrated in Figure 7. A pure out-of-phase cycle was used in which maximum compression corresponds to the maximum temperature, in which the heating and cooling rates were $8.5\text{ }^{\circ}\text{C s}^{-1}$ with a 10 minute hold at $850\text{ }^{\circ}\text{C}$. A pure out-of-phase cycle was also used to simulate aero engine operation, and in the case the heating rate was $25\text{ }^{\circ}\text{C s}^{-1}$ to $1100\text{ }^{\circ}\text{C}$ with a 10 second hold period followed by cooling at about $12\text{ }^{\circ}\text{C s}^{-1}$.

September 2001

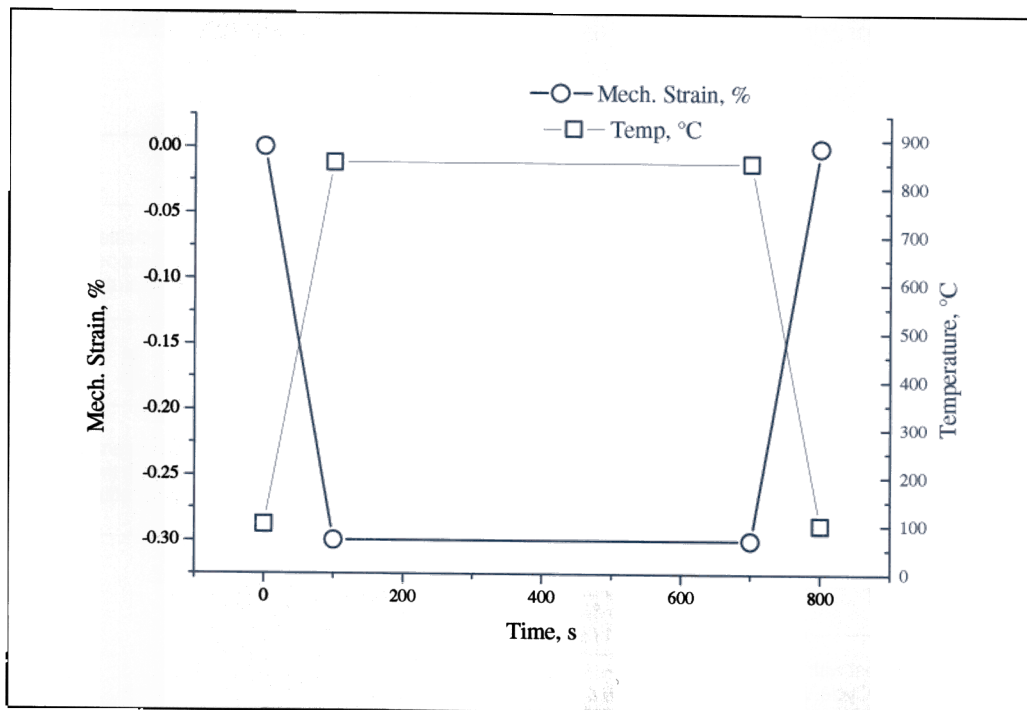


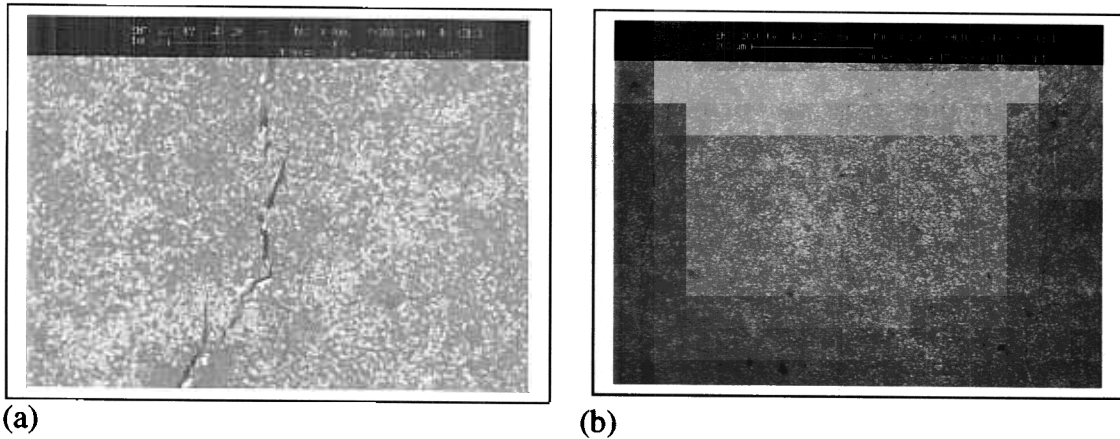
Figure 7 An industrial TMF out-of-phase cycle

It was hoped that fracture of the coating could be detected using acoustic emission (AE) using a Fecralloy[®] waveguide spot-welded to the grip end of the sample. Unfortunately the hydraulic system proved to be too “noisy”, and as will be seen later the type of failure observed would not be expected to generate significant acoustic signals. Furthermore it was also believed that failure could be defined by a fall in the maximum (tensile) load at the coldest part of the cycle, but again this proved not be a reliable indication of coating cracking. Thus cracking was detected by visual inspection of the sample using a scanning electron microscope at intervals during the test. Crack initiation was confirmed metallographically by inspecting the sample in a scanning electron or light microscope.

4 RESULTS

A number of trials were carried out with uncoated IN738 and CMSX4 in order to check its operation. During this work with IN738 it was observed that large plastic deformation occurred at temperature above 850 °C when using the industrial cycle with a 10 minute hold at maximum temperature. Thus all tests with the industrial cycle were limited to 850 °C. With almost all coated IN738 samples the bulk alloy fractured, and after examination of the fracture section it could be seen that the fracture was associated with porosity which was probably derived from the casting process. Figure 8 shows micrographs of the surface of one such fractured sample, where it can be seen that the coating (CN91) was unaffected during the test.

September 2001



(a) (b)
Figure 8 Scanning electron micrograph of IN738 sample coated with CN91 after 262 cycles in the industrial TMF cycle at 850 °C, (a) fractured region (b) uncracked coating

The most successful tests were with coatings applied to CMSX4, and here two industrial and one aero cycle test were performed with SE20 and TM312 coatings. Figures 9-11 show scanning electron and optical micrographs of surface cracking and cross-section through the exposed samples. The cross-sections show that there was significant oxidation during the tests despite the presence of an inert atmosphere. Furthermore, in no case did the crack penetrate into the substrate.

Table II: Coating Behaviour in TMF Out-of-Phase Tests

Coating system	TMF test cycle, temp °C	No of cycles	Observation
CMSX4/SE20	Industrial, 850	324	
		648	
		1348	
		1371	
		1803	<i>cracked</i>
CMSX4/TM312	Industrial, 850	400	
		800	
		1100	<i>cracked</i>
CMSX4/SE20	Aero, 1100	66	
		423	
		500	<i>cracked</i>

September 2001

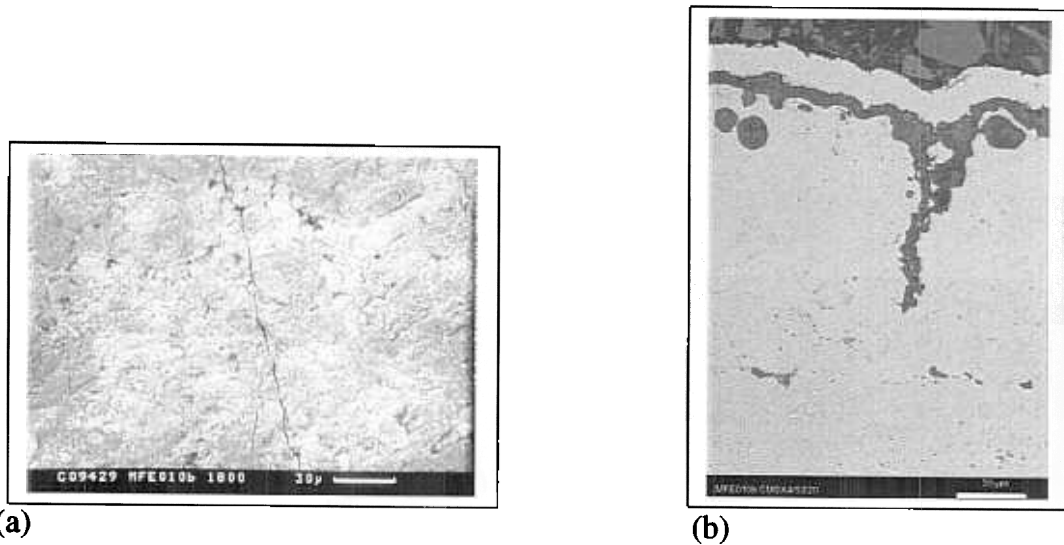


Figure 9 (a) Scanning electron micrograph of the surface CMSX4 coated with SE20 after 1800 cycles in the industrial out-of-phase TMF cycle at 850 °C, and (b) an optical micrograph of a cross-section through a cracked region of the same sample

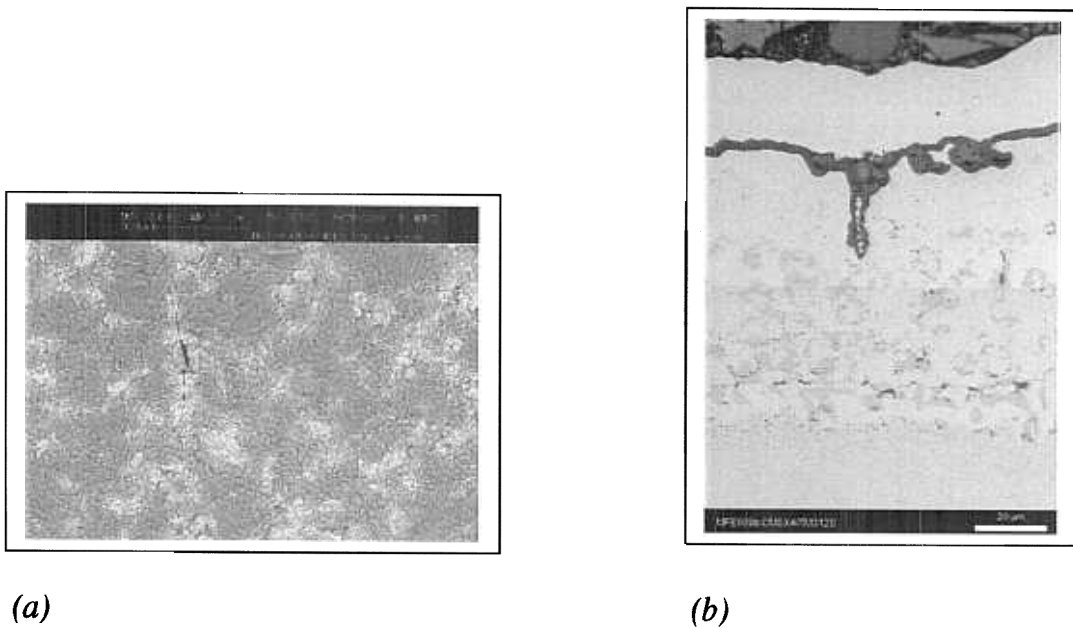


Figure 10 (a) Scanning electron micrograph of the surface CMSX4 coated with TM312 after 1100 cycles in the industrial out-of-phase TMF cycle at 850 °C, and (b) an optical micrograph of a cross-section through a cracked region of the same sample

September 2001



Figure 11 Scanning electron micrograph of the surface CMSX4 coated with SE20 after 500 cycles in the aero out-of-phase TMF cycle at 1100 °C.

This data set is somewhat limited so that it is difficult to make comparisons, but it would seem clear that SE20 has superior TMF resistance to TM312, while the aero TMF cycle caused significantly more damage than the industrial cycle used in this work. An attempt to make additional comparisons with data in the literature was not successful since most of the TMF data on coated components is concerned with a determination of the effect of coating on the life of the component rather than assessment of the TMF resistance of the coating itself.

It is perhaps understandable that such data are not available in view of the difficulties encountered in this work in detecting the onset of cracking. As stated previously use of acoustic emission (AE) and drop in maximum load were investigated as a means of crack detection, but these attempts were unsuccessful. In the case of AE, the hydraulic system generated significant noise and, furthermore, the nature of the crack formed suggested slow crack growth rather than a single event, so that it would be difficult to detect an AE response about the background noise.

The systems that were successfully tested were all MCrAlY type coatings that might be expected to have low load bearing capacity, so attempts to monitor change in maximum load as an indication of coating cracking would again be difficult.

It is clear therefore that further work is required to develop a crack detection system if the TMF resistance of the coating *per se* is to be determined using this method. While it has been possible to get some measure of TMF resistance using interrupted tests, this is far from an ideal solution.

5 SUMMARY AND CONCLUSIONS

A TMF test facility has been developed and preliminary results have indicated that TMF failures were induced in MCrAlY type coatings. It was not possible, however to develop a means of on-line crack detection, so that data on the number of cycles to initiate coating cracking could only be obtained by use of interrupted tests.

September 2001

For the coatings investigated differences in behaviour were observed when tested under similar conditions, but care should be exercised in interpreting these results due to the very limited data set. It was also clear that, as expected, the aero TMF cycle led to much more coating damage in a reduced number of cycles.

6 ACKNOWLEDGEMENTS

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