Informal Evaluation of Vacuum-Based Crack Detection Sensor
(Equipment Evaluation)

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Evaluation Report
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EXECUTIVE SUMMARY

This report documents an initial evaluation of a novel vacuum-based crack detection system. The system proved to be easy to set up and operate, and offers an alternative to electrical crack detection and crack growth-monitoring gages.

ACKNOWLEDGMENTS

The author would like to thank Mr. Jack Coate (AFRL/MLSC) for his testing expertise and guidance, including the test fixture design, test operation, and data generation. The author would also like to thank Messrs. John Brausch (AFRL/MLSA) and Dan Laufersweiler (Universal Technologies Corporation) for their nondestructive inspection expertise and guidance, Bob Ware (AFRL/MLSA) for his materials evaluation expertise and data generation, John Rushau and Neil Ontko (AFRL/MLSC) for their testing expertise, as well as Keith McClellan and Duncan Barton of Structural Monitoring Systems (SMS), based in Australia, for the use of their system and technical support.

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PURPOSE

Evaluate the potential of vacuum-based crack detection for the laboratory environment while concurrently developing cracks in turbine engine blades to be used to validate a Probability of Detection (POD) study for a USAF program.

BACKGROUND

Air Force Research Laboratory/Systems Support Division (AFRL/MLS), and several other AFRL organizations, were introduced to a novel technology developed by an Australian company, Structural Monitoring Systems (SMS), in November 2000. Michael Waddell of AFRL/MLO hosted the visit. Following the meeting and demonstration, SMS agreed to provide a complete vacuum-based crack detection system to Ken LaCivita of AFRL/MLSA for an informal evaluation. The equipment and training were provided on 24 January 2001 at AFRL/MLSA.

A prime candidate for the SMS crack detection system was a turbine blade from an aircraft engine that AFRL/MLSA needed to grow small (0.020-0.080 inch) natural cracks for a POD study.

Air Force Research Laboratory/Materials Integrity Branch recently became involved with the development of an eddy current inspection for turbine engine blades on a USAF aircraft. To validate the inspection's POD, blades with varying sizes of flaws were necessary. Unfortunately, only two blades have been found to date with actual cracks present, and both were larger than the required detection size. As a result, the POD would have to be based on Electro Discharge Machined (EDM) notches of the desired lengths (0.020-0.080 inch). The primary concern with this approach was the fact that EDM notches are wider than natural cracks and may not produce the same eddy current response. To resolve this issue, AFRL/MLSA worked with AFRL/MLSC to develop a test program to grow natural cracks in the turbine blades, and the SMS crack detection system was used to monitor crack initiation on the turbine blades.

FACTUAL DATA

The equipment provided by SMS included a constant vacuum source (Kvac) and flow sensing device (SIM), as well as assorted sensors, vacuum lines, and fittings (Figures 1 and 2). Keith McClellan of SMS visited with AFRL/MLS and coordinated a teleconference with Duncan Barton of SMS to provide training and information on the system in AFRL/MLSA's laboratories.

The basic principle the SMS system uses is that a small volume under a steady-state vacuum is extremely sensitive to any leakage, and the resulting change in vacuum due to air ingress is measurable (Figure 3). The Kvac pulls a vacuum on the sensor pad and acts as a reference for a relative pressure measurement. The relative pressure measurement is monitored by the SIM using a low conductance tube to produce a pressure differential between the sensor pad and the Kvac. The sensor pad is a flexible polymer containing channels or galleries molded into one surface (Figure 2). Depending on the particular sensor design, some channels are open to ambient pressure, while others are under a vacuum (Figure 4). The spacing of the channels on the sensor defines the crack size detection limit. The sensors used in this test had channels spaced at 0.020 inch. The surface containing the molded channels is self-adhesive and makes contact with the area being monitored for crack initiation/growth. When a crack grows (Figure 5) long enough to either connect two adjacent channels (vacuum-to-ambient) in the sensor, or between a vacuum channel and an area open to ambient pressure (i.e., edge of sensor), a change in pressure differential occurs.

The sensor adhesive was evaluated with X-ray fluorescence and Fourier Transform Infrared spectrometry, and was not found to contain any constituents (i.e., halides) that would promote stress corrosion cracking in the turbine blade Inconel 713 material.

The engine manufacturer provided several scrap engine turbine blades for testing purposes. The blades were acceptable for testing since the cause for rejection was primarily from defects along the leading edge of the blades, while the testing would attempt to grow cracks along the blade trailing edge.

The cyclic testing was performed in AFRL/MLSC's structural test facility. Following preliminary setups to determine the optimum loading application and fixturing, a three-point bend test was chosen (Figure 6). After proper surface prep, consisting of an acetone wipe of the mounting surface, the sensor was applied to the area of interest (Figure 7) on the concave side of the blade. Once the blade was mounted into the test fixture, the test engineer loaded the blade on its concave side at its midspan until a noticeable deflection was produced. The test loading was run at 10 Hz and every 10,000 cycles the load was increased by 10 pounds. Although the SMS system had an audible alarm, it was not effective over the background noise of the test lab. An option to wire the SMS system into the test equipment to provide an automatic test interrupt was considered but was not practical for this particular test. As a result, a test operator observing the digital readout on the SIM monitored the test. The test was stopped when the system measured vacuum pressure differentials in excess of 200 Pa, an arbitrary value recommended by SMS.

DISCUSSION

The primary goal of the evaluation was to determine if the SMS sensor would have any advantages or unique applications when compared to other laboratory crack monitoring equipment already in use by AFRL/ML. The secondary goal was to grow small natural cracks on the trailing edge of engine turbine blades.

Typically, the AFRL/MLSC Structural Test Laboratory uses one of three primary means of detecting crack initiation and monitoring crack growth:

a. Fractomats–Thin layers of conductive material are bonded to the test specimen in the area of interest. Current is applied to the fractomat. A tear in the fractomat resulting in a change in resistance will match a crack in the specimen. The subsequent voltage change indicates the presence of the crack. Changes in crack lengths as small as 10^{-8} inches can be measured.

b. EPD (Electro Potential Difference)–Basically the same concept as a fractomat, except the current flows through the specimen. Test leads are soldered/brazed onto either side of area of interest. Again, changes in crack lengths as small as 10^{-8} inches can be measured.

c. Visual–Self-explanatory, using lighting and magnification. Can typically detect cracks as small as 10^{-4} inches, but very manhour intensive.

These three methods usually suffice for ASTM type testing on test coupons with a starter notch. Specimens are typically flat plates or dog-bone specimens. When a complex geometry is tested that does not lend itself to the first two methods, visual is typically used. Also, with these techniques, the location of the crack is known (e.g., due to the starter notch).

However, this test was attempting to grow a small natural crack without the help of a starter notch. A starter notch would invalidate the eddy current response from a natural crack. As a result, the exact location of crack initiation would be unknown and the time to initiation could vary significantly from test to test. The lack of a starter notch made the fractomat and EPD methods nonapplicable, and visual detection had a low probability of being able to detect a crack before it grew beyond the desired size.

Other methods that have potential for performing this task, but were not evaluated in this testing, include crack detection gages and the Meandering Winding Magnetometer (MWM) array:

a. Crack detection gages - Typically consist of a single strand of high-endurance alloy. A crack propagating beneath the gage will induce local fracture of the sensing strand and open the electrical circuit.[1]

[1] Micro-Measurements website www.measurementgroup.com/guide/500/lists.

b. MWM array-A "planar", conformable eddy current sensor. The array induces electrical current into the part to detect discontinuities and, therefore, is limited to conductive materials.[2]

These methods are not used in the AFRL/MLSC structural test laboratory because most of the testing performed in AFRL/MLSC is American Society for Testing and Materials (ASTM) type testing as mentioned earlier.

Several types of SMS sensors are available. The sensor used for this test was designed specifically for crack initiation detection, having two manifolds (one vacuum and one ambient) that will detect any crack that bridges the two manifolds, as explained in the Factual Data section. Other variations of the sensor can be configured with numerous manifolds and multiple-channel monitoring, which would allow measurement of crack growth rates as well, by detecting presence of the crack as it grows past each successive manifold.

In total, six blades were tested. Although the SMS system detected every crack generated by the testing, the unique experimental approach to grow cracks without a starter notch resulted in some unusable results. Some blades were overloaded, and some exhibited crack growth that was too rapid to detect and stop before the crack grew beyond the desired limit. Also, in some cases the sensors detected indications that did not appear to be visible cracks, but upon closer examination, were found to be microcracking (Figure 8). Due to the finite number of test articles, some blades had to be retested with the load applied at different points along the trailing edge. As a result, this introduced another variable that made load level determination even more challenging.

Testing resulted in two blades containing cracks in the desired range and in the desired region. These cracks were verified with nondestructive inspection (NDI) including visual, eddy current, and dye penetrant. Figures 9 and 10 illustrate the cracks detected in these two blades. No "false calls" occurred. Based on these limited test results, the sensors proved the capability to detect cracks 0.020" and larger, and may also be sensitive enough to detect microcracking. The reliability of the sensor could not be assessed due to the means used to generate cracking.

A potential future application of the SMS system would be on-aircraft crack initiation detection and crack monitoring in localized areas. However, on-aircraft applications in the USAF currently do not use any type of crack detection or crack monitoring gages due to reliability concerns. The primary concerns are false calls or malfunctioning gages driving an unnecessary inspection. Other methods currently

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[2]Surface-Mounted Eddy-Current Sensors for On-Line Health Monitoring of Fatigue Tests and for Aircraft Health Monitoring; Neil Goldfine, Darrell Schlicker, Andrew Washbaugh, JENTEK Sensors, Inc.; Second Joint NASA/FAA/DoD Conference on Aging Aircraft, Aug 1998

available that provide similar capability (i.e., 0.010 inch crack length resolution) are crack propagation gages. Crack propagation gages typically consist of a number of resistor strands connected in parallel.[3] When bonded to a structure, progression of a surface crack through the gage pattern causes successive open circuiting of the strands, resulting in an increase in total resistance. The SMS system offers an alternative to the electrical propagation gages should a specific application prohibit an electrical gage. However, before the SMS system is used on aircraft, extensive environmental testing would be required to prove the sensors and/or system could withstand the aircraft-operating environment (i.e., fluids, temperature extremes, vibration, etc.). Also, the operating performance of specific system configurations would have to be evaluated (i.e., longer lengths of vacuum lines may reduce sensitivity, etc.)

CONCLUSIONS

The SMS system proved to be capable of detecting crack initiation. Cracks as small as 0.020 inch were successfully detected during the AFRL/MLSA testing, using sensors with 0.020 inch spacing between vacuum channels. SMS has sensors with spacing as small as 250 microns (0.010 inch) that should be able to detect cracks as small as 0.010 inch.

Crack sizes generated in testing are dependent on the crack growth rate. When cracks grow too fast, the test operator may not have enough time to react to stop the crack from growing beyond the desired size.

In some instances, the SMS system may also detect microcracking that may or may not be desirable for a particular test.

Air Force Research Laboratory/Systems Support Division's experience was limited to the simplest version of the sensor, which contains two multi-channel manifolds. This particular configuration is ideal for detecting surface crack initiation on nearly any material in the laboratory environment. Other versions of the sensor can be configured to monitor crack growth.

The SMS system provides an alternate means of surface crack initiation detection and crack growth monitoring for the laboratory environment. Like other crack detection gages, this system has an advantage over some crack monitoring methods, such as fractomats and EPD, because a large area of complex geometry can be monitored for crack initiation, even without knowing the precise initiation location (i.e., no starter notch). The system is applicable to nearly any material that has surface breaking flaws.

The SMS sensors is not recommended for the ASTM type testing performed in AFRL/MLSC since fractomat and EPD methods are an order of magnitude more sensitive.

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[3]Micro-Measurements website www.measurementgroup.com/guide/500/lists.

A potential application for the SMS system is on-aircraft crack initiation and crack growth monitoring outside of the USAF. Extensive environmental testing and evaluation of system configurations is recommended prior to this application.

RECOMMENDATIONS

The system would benefit from a stand-alone alarm system that is audible in a laboratory environment and/or a flashing beacon that could be placed in an area that is readily seen from around the laboratory. The option to wire the system and test equipment for automatic test interrupt is ideal, but is more suited to equipment that would have a dedicated SMS system.

The system is currently limited to the laboratory environment, but has potential as an on-aircraft crack detection/monitoring system for airframe or engine structure/components. Since the USAF is currently reluctant to depend on crack detection sensors for operational aircraft, there is no guarantee that any amount of testing could change this mind set. The following additional testing is recommended should SMS decide to pursue on-aircraft crack detection:

- Reliability testing which demonstrates near 100 percent crack detection and zero false calls in an operational environment.

- Environmental testing to prove the sensors could withstand the operational environment on an aircraft (i.e., exposure to fuels and oils, temperature extremes, etc.).

- Verification that the sensor adhesive does not interact with various aircraft materials. Note: Preliminary chemical analyses indicated the adhesive did not adversely affect the Inconel 713 material tested.

- Evaluation of length of vacuum line and sensitivity of sensor, since some applications could require extensive lengths of vacuum line to make an on-aircraft system practical.

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FIGURES

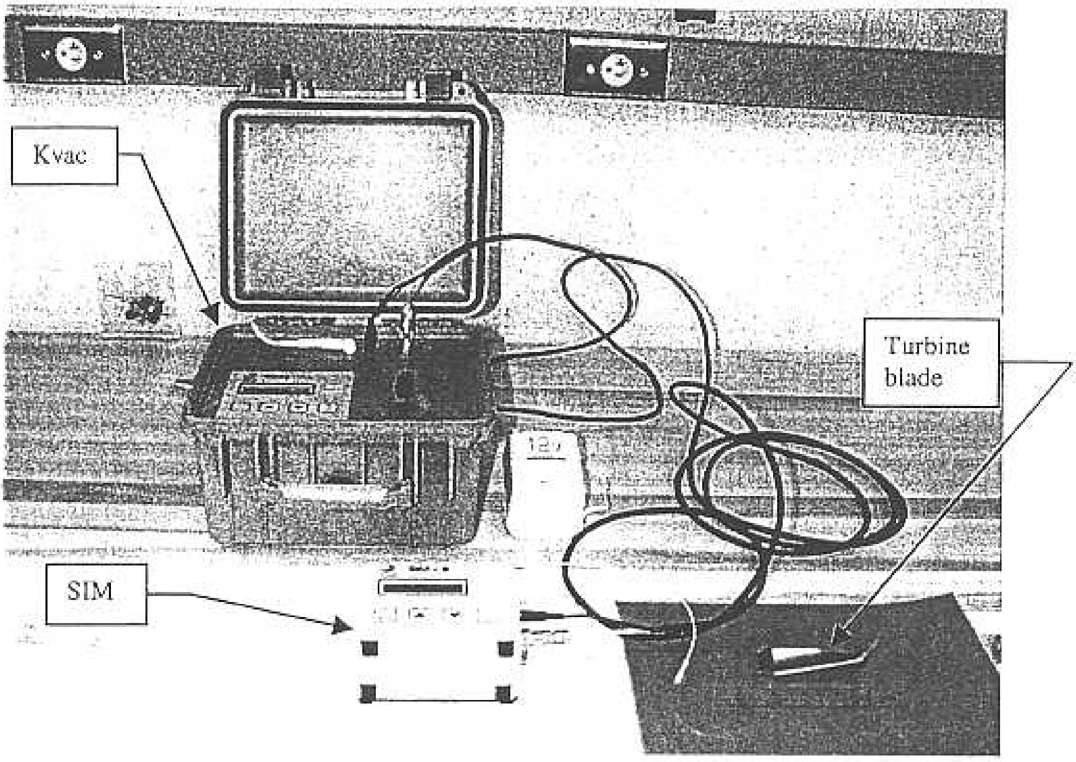

Figure 1. SMS vacuum-based crack detection system.

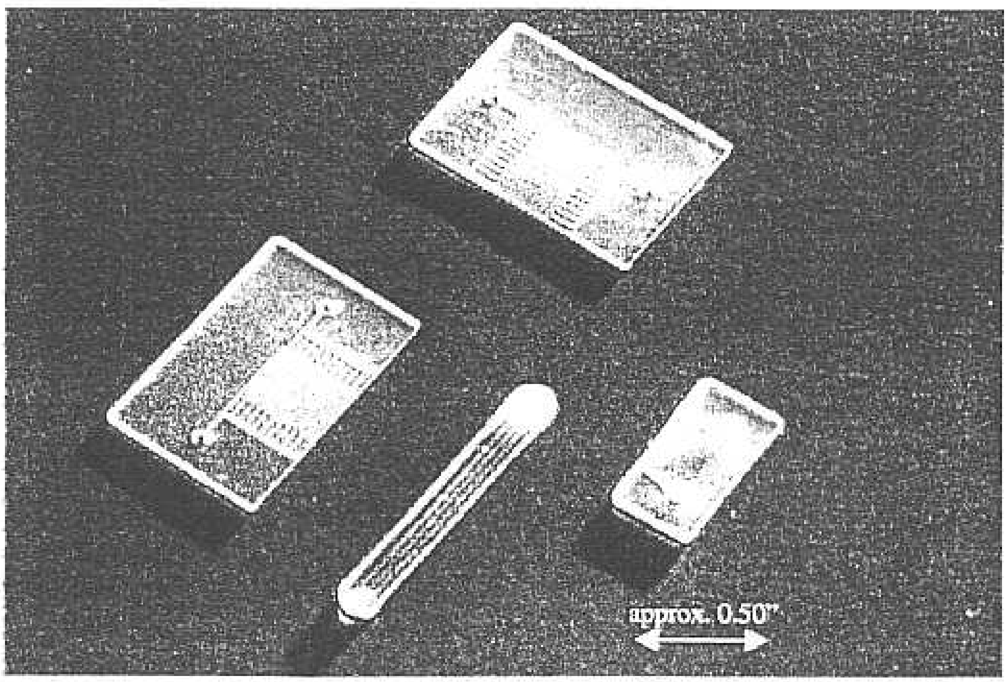

Figure 2. Typical sensors.

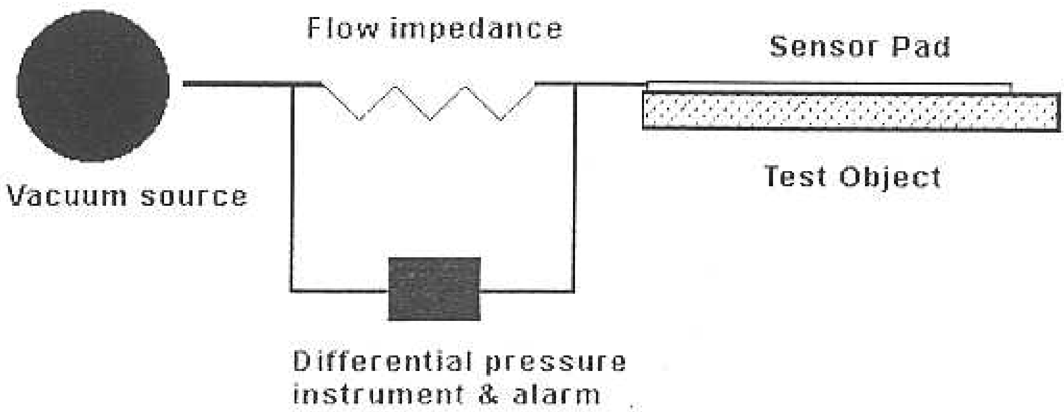

Figure 3. System schematic.

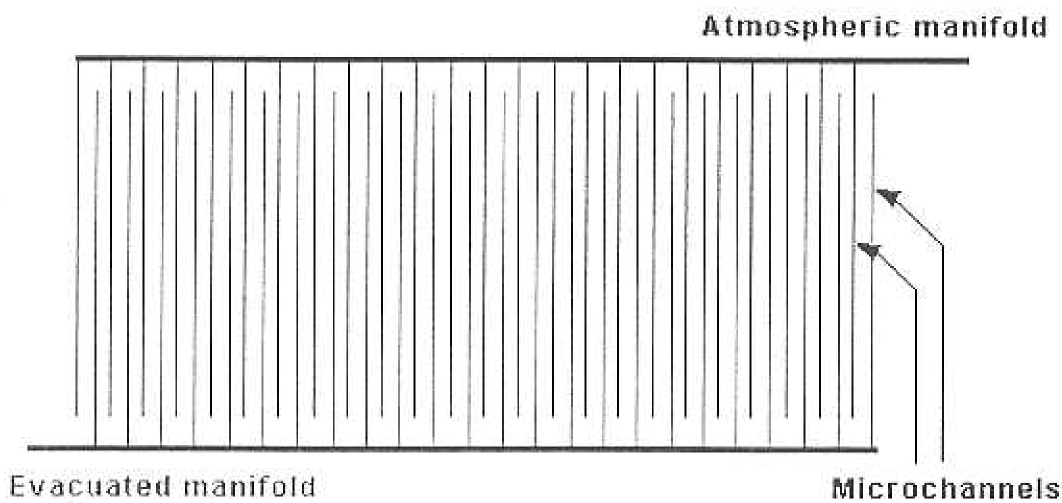

Figure 4. Sensor manifolds.

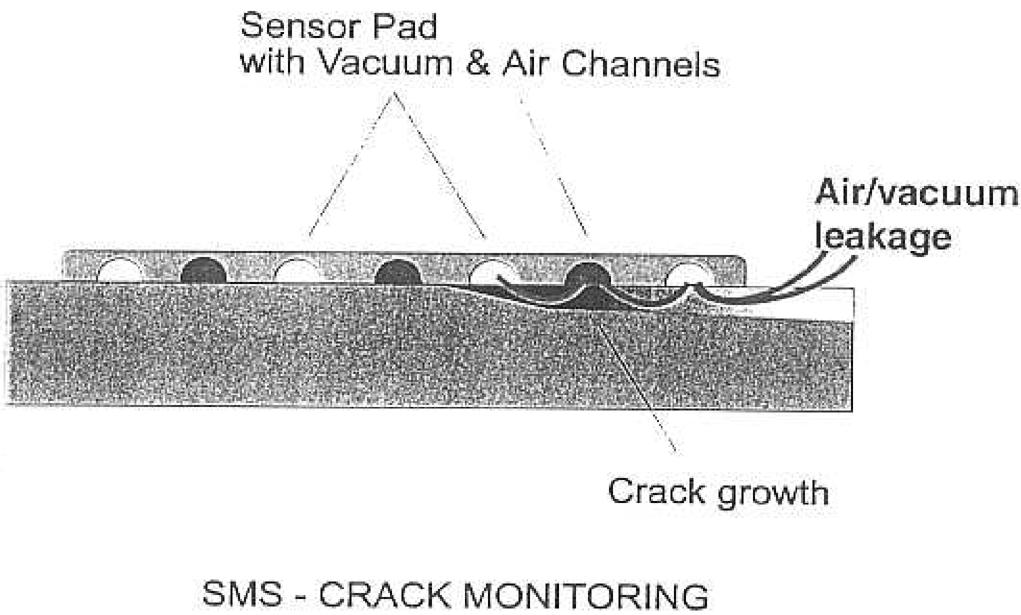

Figure 5. Crack growth beneath sensor.

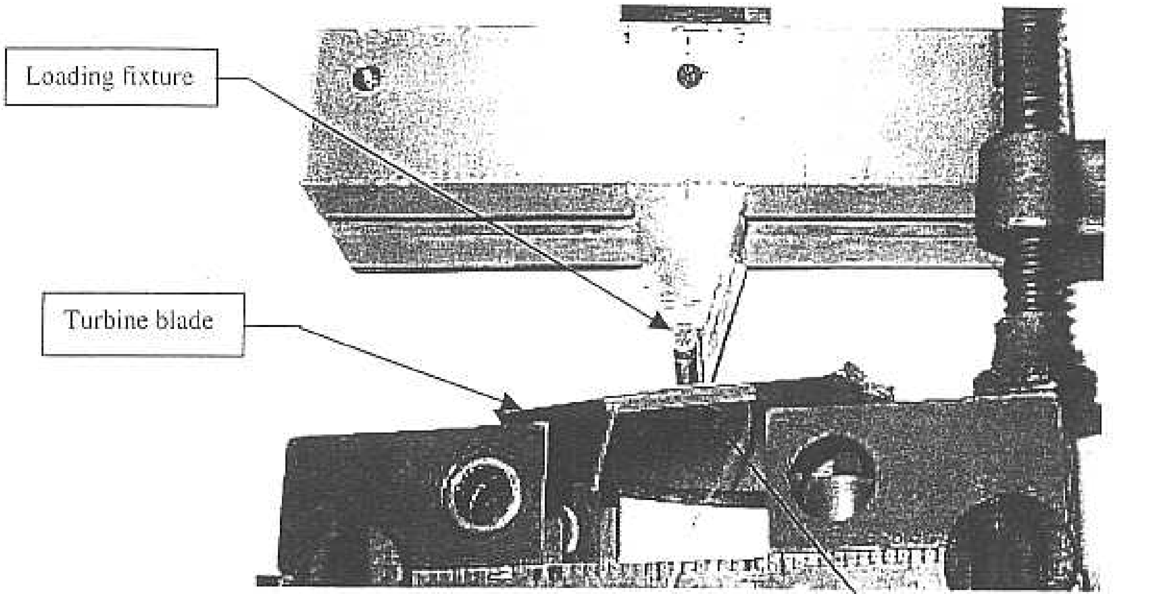

Figure 6. Three point bend cyclic

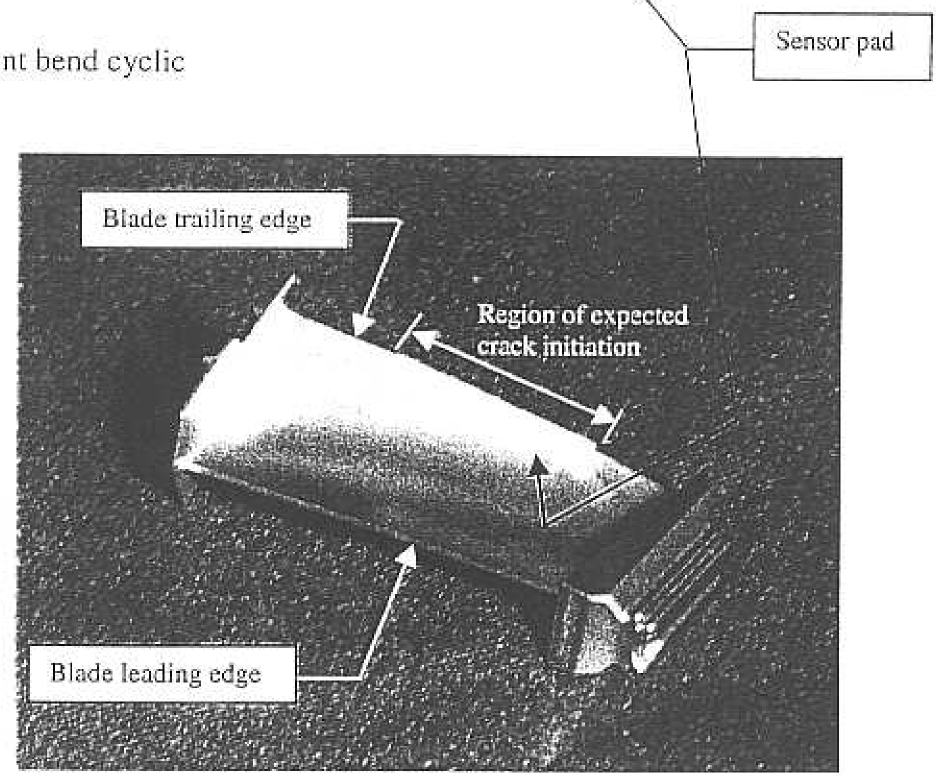

Figure 7. Turbine blade with SMS sensor

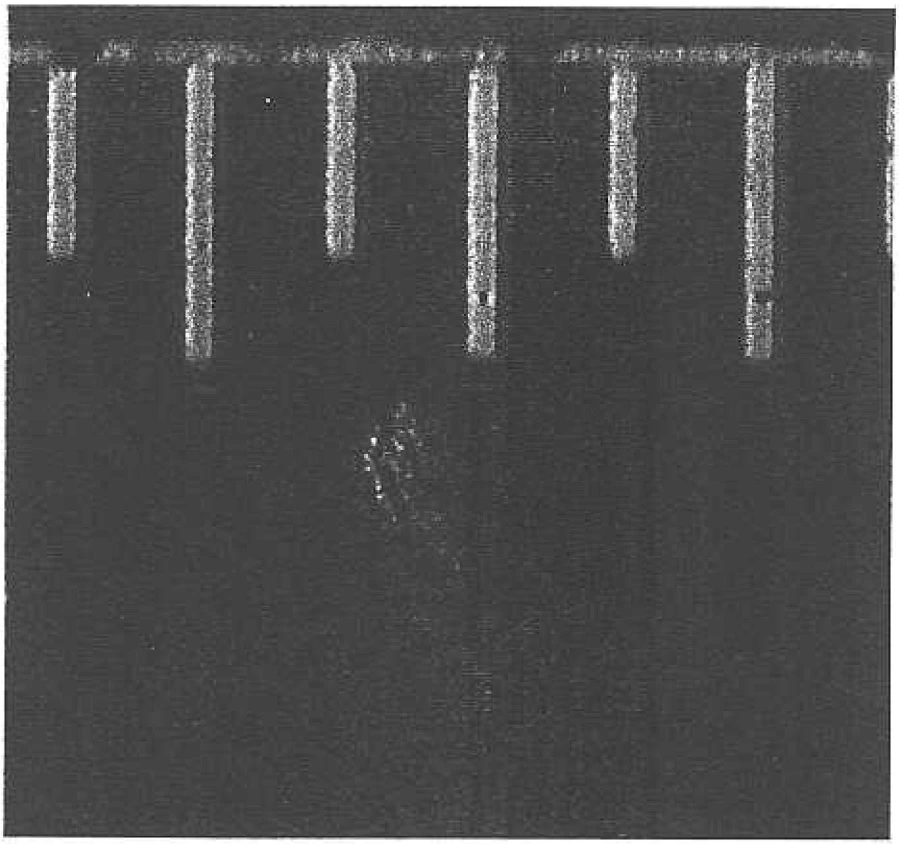

Figure 8. Microcracking detected by SMS sensor (small divisions = 0.063 inch).

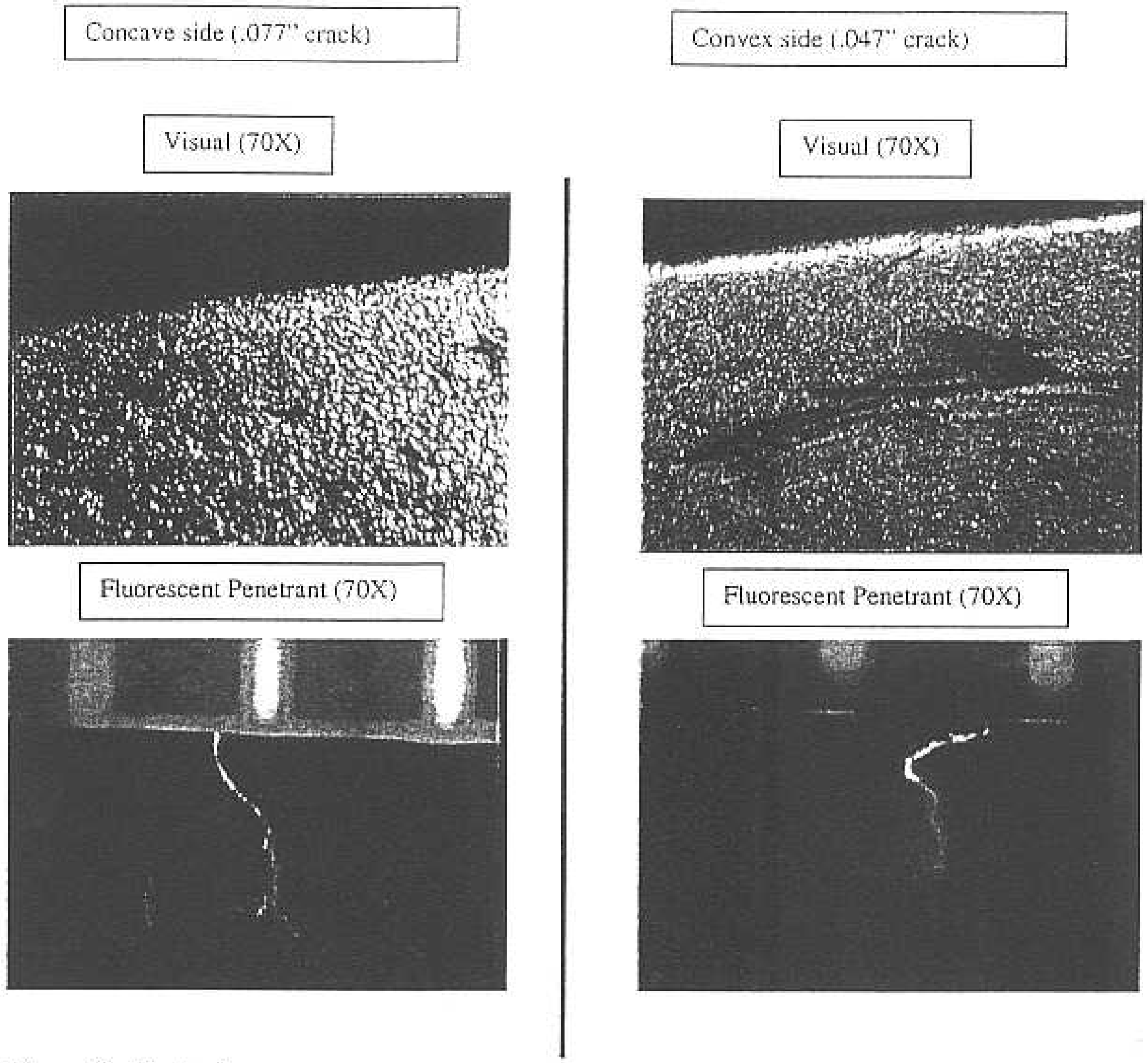

Figure 9. Blade 1.

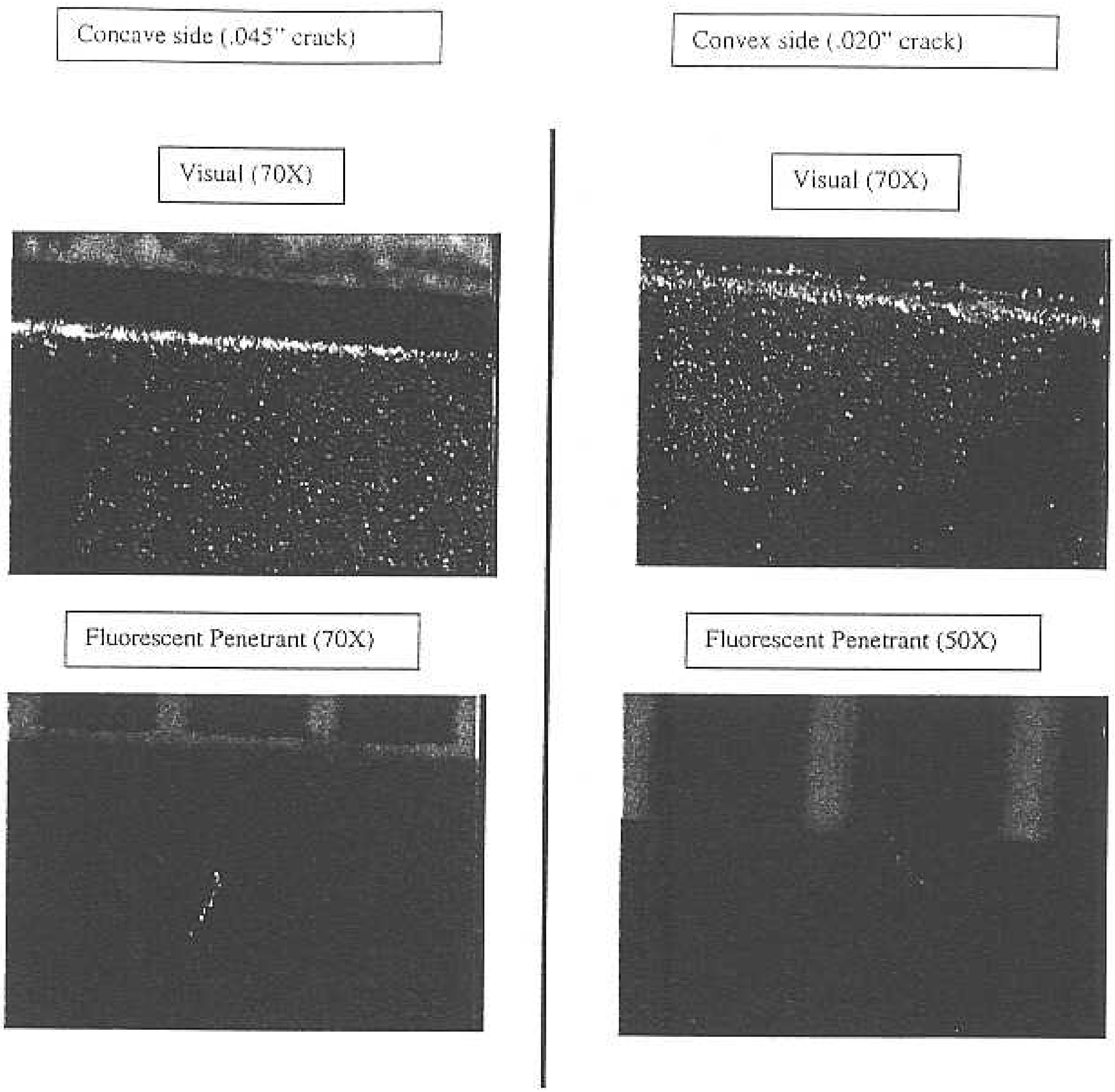

Figure 10. Blade 2.