THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

94-GT-298

AIRCRAFT CRASH CAUSED BY STRESS CORROSION CRACKING

H. J. Kolkman, G. A. Kool, and R. J. H. Wanhill
Department of Materials
National Aerospace Laboratory, NLR
Emmeloord, The Netherlands

ABSTRACT

An aircraft crash in the Netherlands was caused by disintegration of a jet engine. Fractography showed that the chain of events started with stress corrosion cracking (SCC) of a pin attached to a lever arm of the compressor variable vane system. Such a lever arm - pin assembly costs only a few dollars. Investigation of hundreds of pins from the accident and a number of identical engines revealed that this was not an isolated case. Many pins exhibited various amounts of SCC. The failed pin in the accident engine happened to be the first fractured one.

SCC requires the simultaneous presence of tensile stress, a corrosive environment and a susceptible material. In this case the stress was a residual stress arising from the production method. There was a clear correlation between the presence of salt deposits on the levers and SCC of the pins. It was shown that these deposits were able to reach the internal space between the pin and lever arm, thereby initiating SCC in this space. The corrosive environment in Western Europe explains why the problem manifested itself in the Netherlands at a relatively early stage in engine life. The main point is, however, that the manufacturer selected an SCC-prone material in the design stage. The solution has been to change the pin material.

INTRODUCTION

Recently an aircraft powered by a single turbofan jet engine crashed in the Netherlands. An initial investigation revealed that the crash was due to disintegration of the jet engine. Destroyed blades and vanes were found from the sixth compressor rotor stage onwards. This made the fifth stator stage - located in front of the sixth rotor stage - particularly suspect.

The third, fourth and fifth compressor stator stages of the engine under consideration contain variable stator vanes. The variable vanes are connected to the actuator rings by means of levers. Each lever is an assembly of an arm and a pin, see Fig. 1. The pins fit into the holes of an actuator ring. One of the fifth stage levers exhibited a broken pin. The fracture face was along AA in figure 1. A fractographic investigation was performed in order to determine whether the pin failure was a consequence or the cause of the crash.

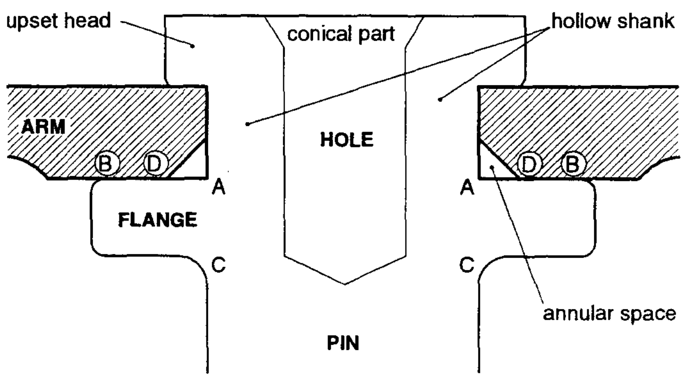

Fig. 1 Schematic cross-section of the vane arm assembly

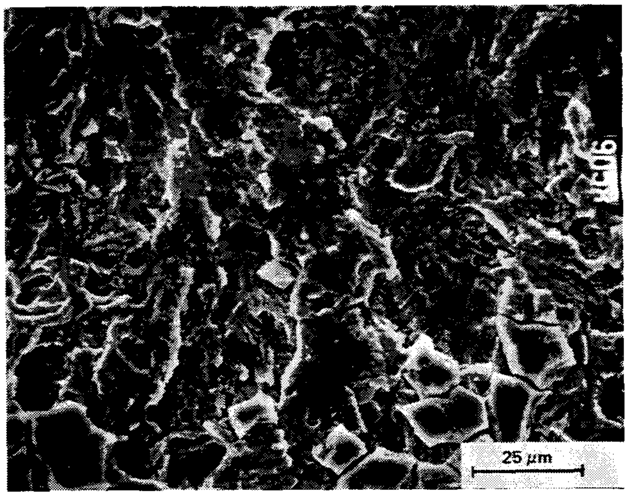

Fig. 2 Example of corrosion products on top of transcrystalline stress corrosion cracking (SCC) of the pin

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
The Hague, Netherlands — June 13–16, 1994
This paper has been accepted for publication in the Transactions of the ASME
Discussion of it will be accepted at ASME Headquarters until September 30, 1994

FRACTOGRAPHY

Macroscopic study of the fracture face revealed that little deformation had taken place, and the fracture face was very flat. In other words, it was highly unlikely that the fracture was created by overload during the crash. The fracture face of the pin was studied in more detail by means of SEM (Scanning Electron Microscopy). It was found that almost the entire fracture face showed the characteristics of transcrystalline SCC (Stress Corrosion Cracking); see Fig. 2. Characteristic corrosion pits, tunnels and slots [1, 2] were found near both the pin inner and outer perimeters; see Fig. 3.

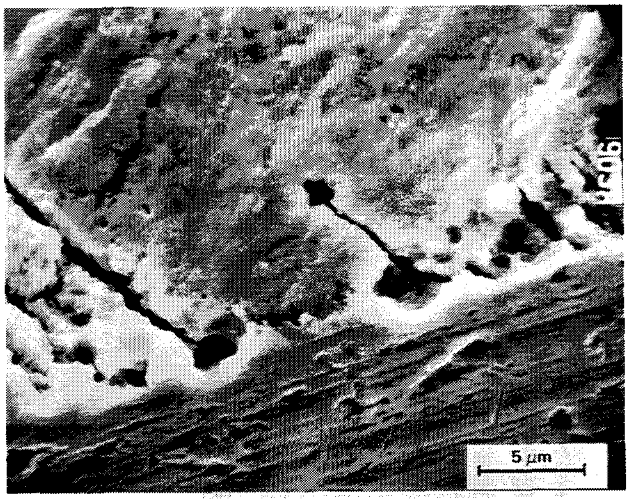

Fig. 3 Example of corrosion pits and slots. The lower part of the fractograph shows the inner perimeter and part of the surface of the central hole in the pin

SCC TESTS

SCC requires the simultaneous presence of:

- a (tensile) stress
- a susceptible material
- a corrosive environment.

Initially it was unclear whether and how all these conditions were fulfilled. The driving stress for SCC might be the residual stress introduced during the upsetting of the pin heads. But it was unknown whether this stress was high enough to initiate SCC. The pin material was the nitrogen-strengthened stainless steel Nitronic 60. No definitive literature data on the SCC susceptibility of Nitronic 60 could be found [3, 4]. The West European environment is certainly corrosive, e.g. [5, 6]. However, in view of the manufacturing process it was supposed that the annular space (see Fig. 1) - where the SCC cracks initiated - was (mechanically) sealed from the environment. In that case the corrosive medium would have to have been introduced during the production process, e.g. by cleaning with chloride containing solvents or by a chloride containing grease used during the upsetting.

In view of these uncertainties it was decided to perform SCC-tests according to ASTM Standard Practice G36-87, which involves exposure in boiling $MgCl_2$. The test articles were 15 levers, including some new ones. No external stresses were applied. The test duration was seven days. After the test the pins of all levers exhibited cracks and $MgCl_2$ was found in all internal spaces investigated. This shows that:

- the required stress for SCC was the residual stress arising from the production method
- Nitronic 60 is prone to SCC
- the internal annular space was not sealed from the environment. Hence it is possible that the corrosive environment penetrated into these internal spaces. Evidence that this really occurred during service will be given later.

CONDITION OF UNFAILED PINS

Quantitative results

A major point of concern was whether an isolated case was concerned. Hence a number of techniques were used to investigate whether SCC had been active in other pins of the accident engine as well as other identical engines of the same user. After it became clear from laborious metallographic sectioning that a number of unfailed pins exhibited SCC, it was decided to:

1) Inspect all levers frequently.
2) Continue the investigation to determine whether the occurrence of SCC was dependent on factors such as the vendor of the levers, the compressor stage or the service life.

X-ray inspection was found to be very unreliable due to the complicated geometry. Optical metallography of cross-sections through the pins could also give unreliable results for other crack geometries than perfectly annular, and also the preparation of cross-sections of hundreds of pins would have been very time-consuming. The engine manufacturer came up with the excellent idea to perform tensile tests on the pins, using a simple jig fitting with the grips of the tensile machine. Hydraulic grips enabled a rapid change of the test articles. 643 pins were tensile tested.

There were different pin failure types, namely:

- Failure of the hollow shank (88 pins)
  This fracture type occurred when an stress corrosion crack of some length was already present in the plane AA in Fig. 1. Figure 4 illustrates the resulting fracture face. The dull pre-existing SCC can be clearly distinguished from the shinier grey overload area caused by the tensile test. The amount of SCC could be quantified by determining the percentage of SCC in the fracture face by means of an image analyzer or from the decreased fracture load, or by measuring the maximum stress corrosion crack length (as percentage of the wall thickness).
- Shearing of the upset head (550 pins)
  This fracture type occurred mainly when no stress corrosion crack was present (494 pins). However, more rarely (56 pins) this crack type was also observed if the stress corrosion crack was too small for crack initiation of the shank type, as revealed by careful inspection after the tensile tests. In order to determine the size of these small cracks, a number of them were forcibly opened or cross-sectioned.
- Very rarely (5 pins) sound pins failed in the radius near C in Fig. 1.

Tables 1 and 2 provide examples of the data obtained. It is seen that SCC was found for all variable vane compressor stages in all engines investigated. It might have been expected that the severity of SCC would depend on the stage number and would increase with the number of cycles (which would be very useful in establishing an inspection interval), but such tendencies were absent.

The manufacturer performed similar tests on pins originating from engines that had been operating in other regions than Western Europe. Severe SCC was found, but only after much longer service lives.

Other observations

- Fig. 4 illustrates the observation that SCC always initiated in the annular internal space.
- On a number of lever arms salt deposits were present, e.g. see Fig. 5.
  EDX (Energy Dispersive analysis of X-rays) in the SEM revealed that these deposits consisted of the harmless $CaSO_4$ and the corrosive NaCl. Because of aerodynamic reasons (stagnation of the by-pass air near obstacles) this salt had not been deposited on all lever arms. There was a close relationship between the presence of these deposits and the

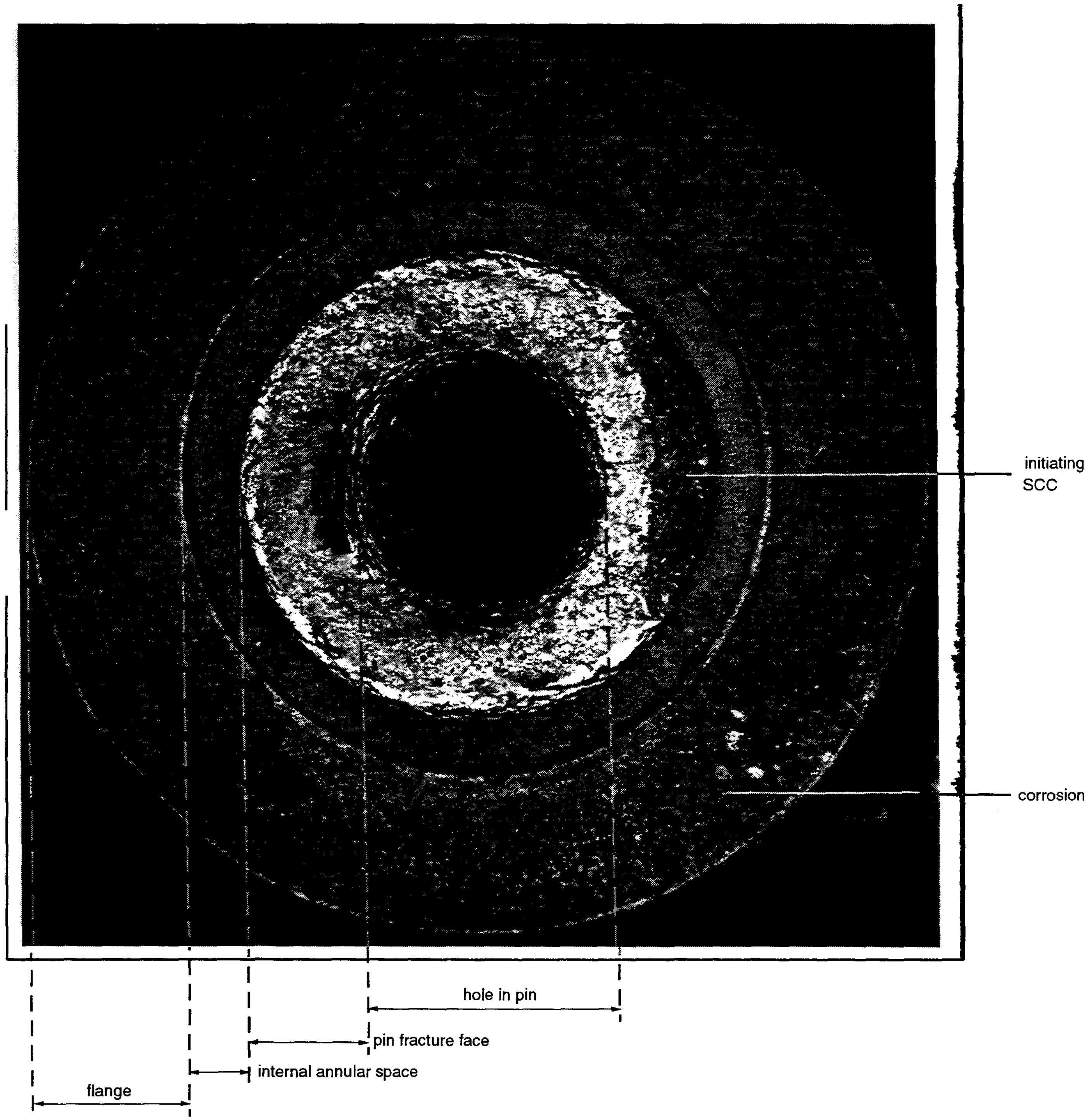

Fig. 4 Result of tensile test. The plane of the photograph is along AA in figure 1; the viewing direction is downwards

Table 1 Number of pins with SCC as fraction of the total number of pins tested

Engine cycles	3th stage	4th stage	5th stage
550	14 %	20 %	13 %
850	9 %	28 %	3 %
1250 (mishap)	20 %	not tested	63 %
1650	20 %	72 %	12 %

Table 2 Maximum area fraction of SCC in fracture face

Engine cycles	3th stage	4th stage	5th stage
550	52 %	64 %	39 %
850	64 %	78 %	< 20 %
1250 (mishap)	11 %	not tested	94 %
1650	86 %	90 %	75 %

Table 3 Relationship between external sals and SCC for the third stage levers of the 850 ccy engine

		pins with		
		SCC	no SCC	Total
arms with	salt	8	10	18
	no salt	0	72	72
	Total	8	82	92

occurrence of SCC, see Table 3.

- For a number of levers the sides of the flanges facing the arms (BD in Fig. 1) were corroded; the other sides of the flanges were always in good condition. There was a close relationship between corrosion of the flange of a particular pin and the occurrence of SCC, Fig. 6. The aforementioned salts were also found on the corroded flanges.
- For some levers many NaCl crystals were found in the internal annular space. Although this observation was relatively rare, it seems unlikely that this NaCl was introduced during production.

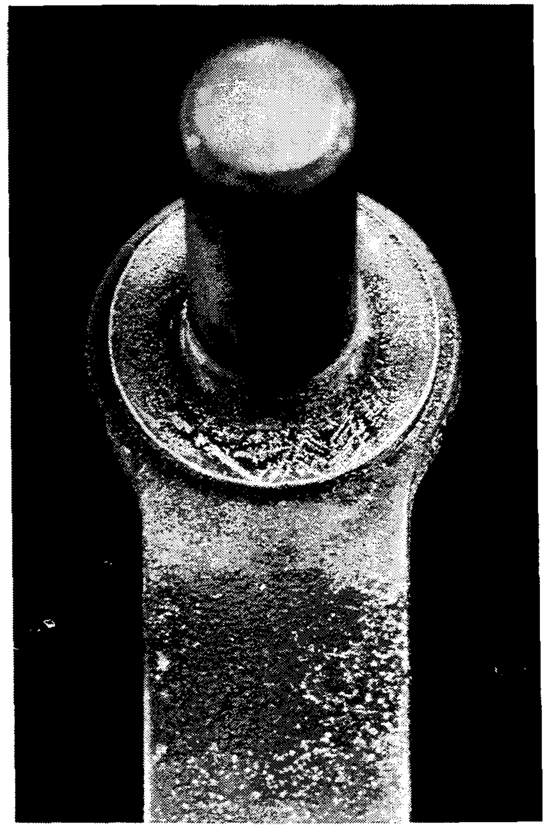

Fig. 5 Extreme example of salt on vane arm

DISCUSSION

From the forementioned observations the following scenario follows. During flight the salt in the by-pass air deposited on a number of lever arms (Fig. 5). During shutdown periods with high relative humidity the deposits absorbed moisture from the air so that a concentrated salt solution was obtained. This salt solution was able to penetrate any opening between the vane arm and the flange of the pin (along BD in Fig. 1). Hence the observed flange corrosion (Fig. 6) can be explained by crevice corrosion of the relatively less noble pin material. Finally the salt solution reached the unsealed annular internal space (see Fig. 1) and supplied the aggressive environment for SCC of pin material in the highly stressed area near A.

The failed pin in the accident engine happened to be the first one. Differences between different engines can be explained by different flight types (e.g. over sea or coastal regions or not) and different humidities during shutdown periods, rather than by differences in service life.

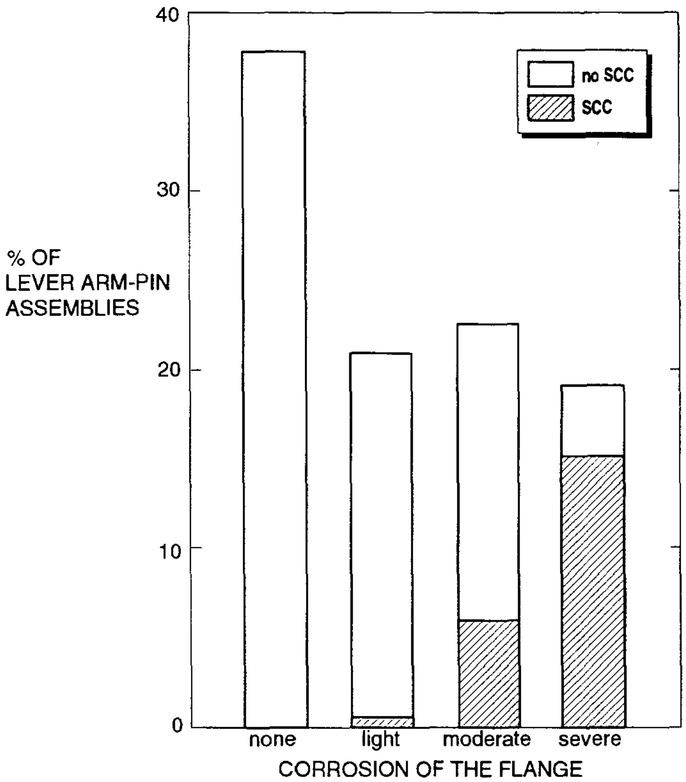

Fig. 6 Relationship between the occurrence of SCC and corrosion of the flange

CONCLUSIONS

The main cause of the crash was that the engine manufacturer selected an SCC-prone material (Nitronic 60) for the pins of the levers of the compressor variable vanes in the design stage. The solution has been to change the pin material. The first levers with the new pin material were delivered less than five months after the accident. The frequent inspections on the levers with the old pins were continued until all these levers had been replaced.

REFERENCES

1. Swann, P.R. and Embury, J.D., "Microstructural Aspects of Stress-Corrosion Failure", pp. 327-363 in "High-Strength Materials", edited by Zackay, V.F., Wiley, New York, 1965.
2. Nielsen, N.A., "Nature of Initial Corrosion of Stressed Stainless Steels by Chloride Ions", Corrosion 20 (1964) pp. 104-109t.
3. Douthet, J.A., "Nitronic Family of Nitrogen-Bearing Stainless Steels", Metal Progress 108 (1975) pp. 50-54.
4. Kirchner, R.W., Crook, P. and Asphani, A.J., "Corrosion Resistant, High Performance Alloys for the Food Industry", Paper 102 in Corrosion 84, NACA, 1984.
5. Kolkman, H.J. and Mom, A.J.A., 1984, "Corrosion and Corrosion Control in Gas Turbines, Part I: The Compressor Section ", ASME Paper 84-GT-225, presented at the 29th Int. Gas Turbine Conference and Exhibit, Amsterdam, 1984.
6. Kolkman, H.J., "Coatings for Gas Turbine Compressors", pp. 224-230 in "Materials Development in Turbo-Machinery Design", edited by Taplin, D.M.R., Knott, J.F., and Lewis, M.H., The institute of Metals, London, Book 456, 1989.