Burst of Steam Turbine Rotor in Nuclear Power Plant

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NITTA, Akito (Central Research Institute of Electric Power Industries)
KOBAYASHI, Hideo (Tokyo Institute of Technology)

(Summary)

At the Hinkley Point 'A' nuclear power station (closed in May 2000) in Somerset located in the southwest part of England, the No. 5 turbine generator suffered a catastrophic failure on September 19th, 1969, 33,360 hours after commercial service was started in April 1965. The failure was caused by spontaneous brittle facture of a shrunk-on low-pressure disc. The No.5 unit was disconnected from the grid for overspeed tests a few minutes before the accident. The failure occurred as the speed reached 3,200rpm. The rotor shaft fractured completely in five positions, and three discs of the low-pressure A rotor came free from the unit. The cause is thought to be stress corrosion cracking (SCC) in a disc keyway. This was the first catastrophic failure of a turbine-generator caused by the brittle fracture of a rotating component in the UK. Fortunately, there were no casualties although seven operators were in the vicinity of the unit at that time.

1. Component

The Hinkley Point 'A' nuclear power station has two Calder Hall type Magnox nuclear reactors and six turbine-generators with a nominal capacity of 87MW. The design conditions of the steam supplied from the reactors were 4.24MPa, 360℃ for a high-pressure turbine, and 1.07MPa, 346℃ for a low-pressure one. As a measure to counter CO2 corrosion of mild steel in the reactor, the steam temperatures were reduced by 10℃ before the accident in 1969. The design rotation speed of the turbines was 3000rpm.

2. Event

At the Hinkley Point 'A' nuclear power station, the turbine-generator of the No.5 unit suffered a catastrophic failure on September 19, 1969, 33,360h after the unit started in commercial service in April 1965. The cross-sectional diagram of the turbine-generator is shown in Fig.1. The failure was caused by spontaneous brittle fracture of a shrunk-on low-pressure disc. Figure 2 shows the appearance of the unit just after the failure. The No.5 unit was disconnected from the grid for overspeed tests a few minutes before the accident. The failure occurred at the time when the rotation speed reached 3,200rpm. The rotor shaft fractured completely in five positions. As shown in Fig.3, three discs of the low-pressure A rotor came free from the unit, and large fragments of them were found scattered in the machine hall. This was the first catastrophic failure of a turbine-generator caused by the brittle fracture of a rotating component in the United Kingdom. Fortunately, there were no casualties although seven operators were in the vicinity of the unit at that time.

The following paragraphs show the results from the Fault Tree Analysis.

(1) Fault tree diagram for mode, mechanism and process of fracture (Fig. 4)

The low-pressure turbine disc, which was the site of the fracture, was made of a 3 Cr-0.5Mo steel by acid open hearth process. Also, the disc was found from chemical analyses to have a high sulfur and phosphorus content, although the levels were within the specifications. Thus, the material was apt to have a lower fracture toughness as a result of the temper embrittlement caused during heat treatment process. Furthermore, in order to shrink the disc onto the shaft, the disc had a semicircular keyway that acted as a stress concentration reservoir. Under such conditions, the stress corrosion cracking (SCC) related to environmental factors such as NaOH in the steam can occur, although it was very difficult to identify the true cause of the SCC. Finally, when the crack reached only 1.6mm in depth, the brittle fracture of the disc occurred.

(2) Fault tree diagram for design and manufacturing errors (Fig. 5)

No problems were found in either the forging and heat treatment processes at the time of the disc manufacture or in the results of nondestructive (i.e., magnetic and ultrasonic) and tensile acceptance tests. Furthermore, review of the design stressing of the main rotating components and investigation of the possible modes of the failure by additional or abnormal stressing did not find any problems in the design. Therefore, the following tests were carried out to identify the root cause of the failure: the detailed fractographic observation of the fractured discs, and chemical analyses, tensile tests, fatigue and crack propagation tests, Charpy impact tests, fracture toughness tests and SCC tests by using the test pieces taken from the discs. From these results, the brittle fracture of the low-pressure turbine was thought to be caused by the initiation and growth of SCC related to environmental factors in the low-pressure steam at the key way (i.e., stress concentrated portion) of the shrunk-on disc, together with the low fracture toughness of the 3Cr-0.5Mo steel made by acid open hearth process.

(3) Event tree diagram for the low-pressure steam turbine rotor burst attributed to the stress concentration in a shrunk-on disc keyway and the low toughness of a disc material (Fig. 6)

The SCC, which was thought to be related to environmental factors in the low-pressure steam, occurred on the bore surface of a shrunk-on disc of 3Cr-0.5Mo steel made by acid open hearth process. The disc keyway was a stress concentration reservoir, and the toughness of the material of the disc was lowered by temper embrittlement during its heat treatment process. The compound effect of these two factors resulted in the brittle fracture of the low-pressure turbine rotor.

3. Course

The No. 5 unit of the Hinkley Point 'A' nuclear power station was disconnected from the grid for overspeed tests a few minutes before the accident. The speed of the unit was raised gradually. A number of operators who were watching the tachometer affirmed that the failure occurred as the rotation speed reached 3,200rpm. At the time, flames came out from the area of the low-pressure turbine together with a loud bang, and within a few seconds an explosion occurred.

At the time of the accident, all six turbine-generators were operational. The No.1, No.2 and No.3 units were not damaged and operation was continued. However, the No.4 and No.6 units were slightly damaged and were temporarily shut down. Fortunately, there were no casualties although seven operators were in the vicinity of the unit at that time. Immediately after the accident, the Central Electricity Generating Board (CEGB) established a formal board of inquiry to conduct a technical investigation into the nature and cause of the failure. The cause was thought to be caused by the SCC in the keyway crown of the disc, and the SCC was observed on many other discs.

4. Cause

The failure was caused by the SCC in the keyway crown. The SCC in the disc bore and keyway was observed on many other discs. The disc made of 3Cr-0.5Mo steel met the material specifications, but its fracture toughness was reduced by temper embrittlement during the furnace cooling after the heat treatment process. Thus, a crack only about 1.6mm in depth was large enough to initiate the brittle fracture because of the stress concentration in the keyway crown.

5. Immediate Action

This failure was the first of its kind to be experienced in the UK. Immediately after the accident, a technical investigating committee was formed of expert representatives from the turbine-generator manufacturers and from the CEGB. After that, numerous examinations, experiments and analyses were strongly conducted to identify the cause of the failure. However, a clear identification of the cause was not reached. It was concluded from circumstantial evidences that the failure was caused by the SCC.

6. Countermeasure

A definite countermeasure was not obtained from the investigations conducted by the technical investigating committee, so additional investigations will be required for establishing preventive actions. However, more general countermeasures, including the elimination of the environmental factors that had contributed to the SCC as well as the adoption of a disc material with higher fracture toughness and a disc without a keyway, were introduced.

7. Knowledge

(1) Stress corrosion cracking is a troublesome form of damage that occurs through the three way combination of material, environment and stress. It is particularly difficult to identify the environmental factors contributing to stress corrosion cracking.

(2) Avoid stress concentration reservoirs in the structural design. If stress concentrations occur, they will cause problems later.

8. Background

No problem was found in the forging and heat treatment processes at the time of manufacturing the discs as well as in the results of nondestructive, tensile and impact tests. Also, after investigating the design stressing of the main rotating components and the possible modes of failure by additional or abnormal stressing, no problems related to the design were found. Therefore, it can be said that there were no technological problems in the design and manufacturing as well as the examinations carried out at that time. On the other hand, it was recognized that some of the discs were made of low- toughness 3Cr-0.5Mo steel processed by the air open hearth method. Also, the shrunk-on disc had a keyway that acted as a stress concentration reservoir. However, although these facts were certainly related to the accident, they were common in the UK and other countries at the time. Thus, no one could foresee the failure from them. In any case, it was the initiation of the SCC that triggered the failure. Stress corrosion cracking is troublesome form of damage that occurs through the three way combination of material, environment and stress. As seen in the result of the failure investigation, it is particularly hard in many cases to identify the environmental factors. In other words, the SCC is an unpredictable form of damage that cannot be prevented completely.

9. Information Source

(1) D.Kaideron, "Steam Turbine Failure at Hinkley Point ' A'," Proc. Instn. Mech. Engrs., Vol.186, pp.341-377(1972).

10. Primary Scenario

01. Ignorance
02. Insufficient Knowledge
03. Poor Experience
04. Production
05. Hardware Production
06. Manufacturing of Machinery and Equipment
07. Low-Pressure Steam Turbine Disc
08. 3Cr-0.5Mo Steel by Air Open Hearth Process
09. Temper Embrittlement
10. Usage
11. Operation/Use
12. Operation of Machine
13. Keyway of Disc
14. Bad Event
15. Chemical Phenomenon
16. Corrosion
17. Failure
18. Fracture/Damage
19. Stress Corrosion Cracking
20. Brittle Fracture
21. Bust of Rotor (Flying-off)

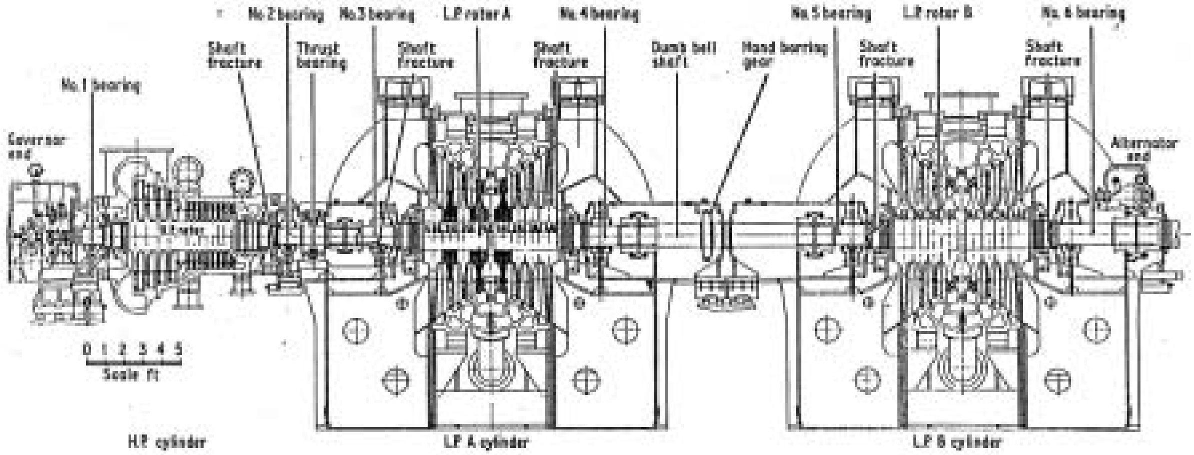

Fig. 1　Overview of the burst TVA Gallatin No.2 IP-LP turbine rotor.

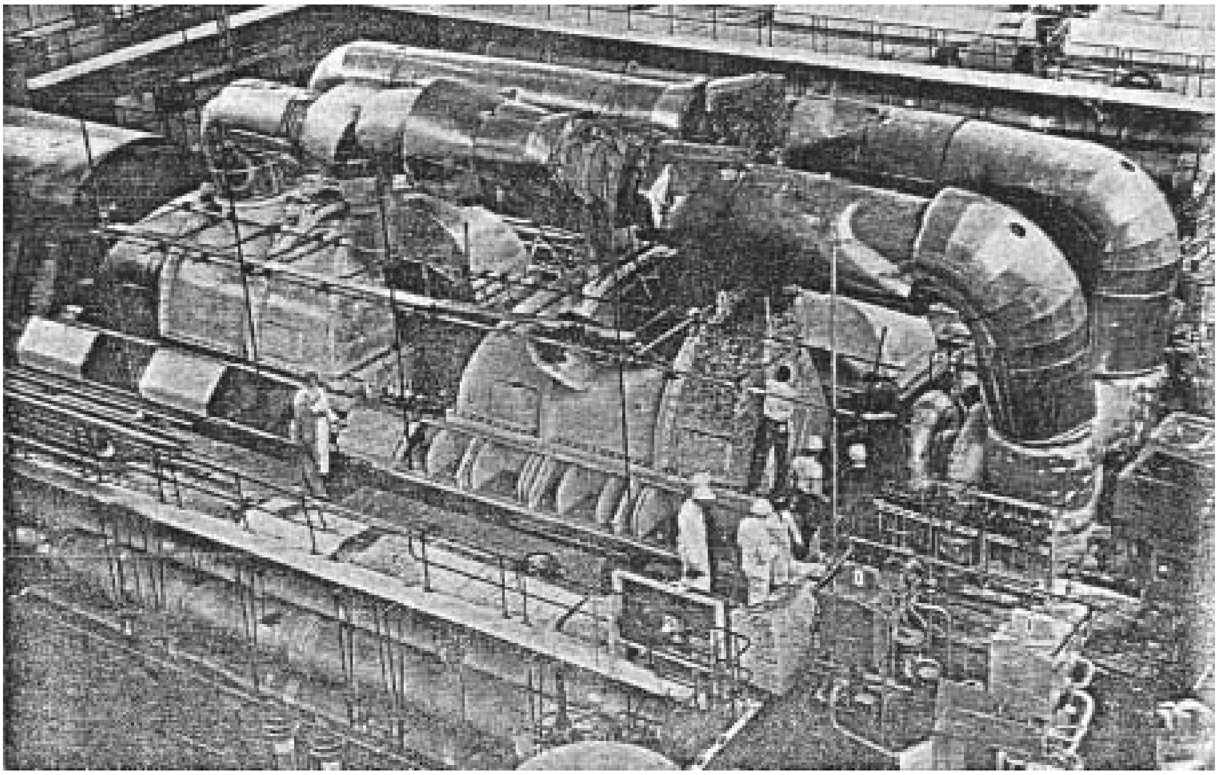

Fig. 2　Appearance of the No.5 unit after the failure.

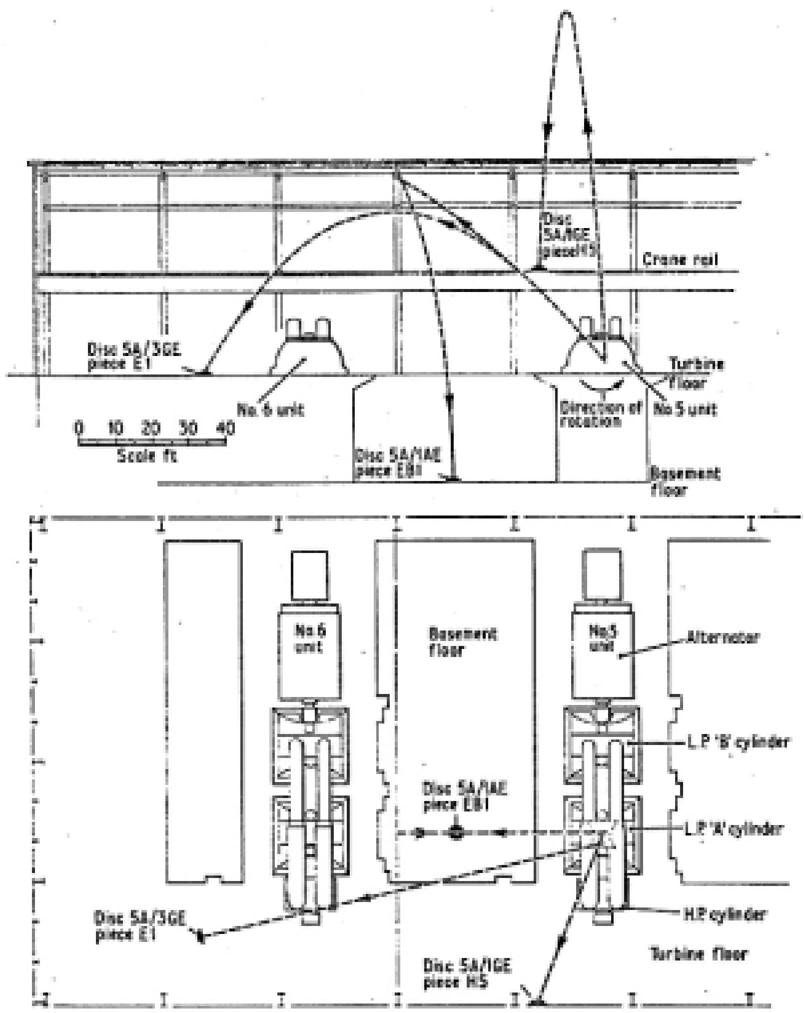

Fig. 3 Flying-off paths of three large disc fragments.

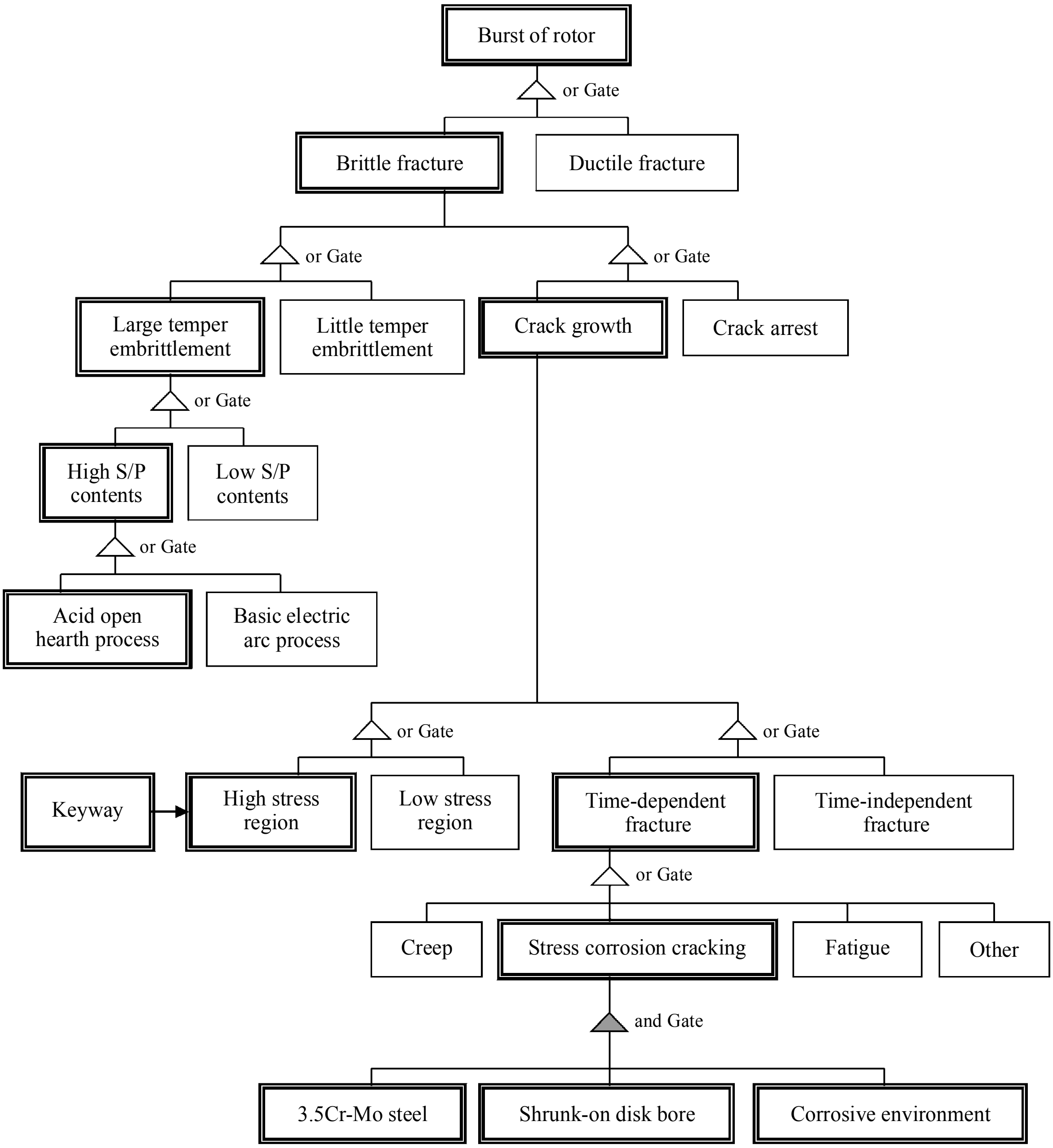

Fig. 4 Fault tree diagram for mode, mechanism and process of fracture.

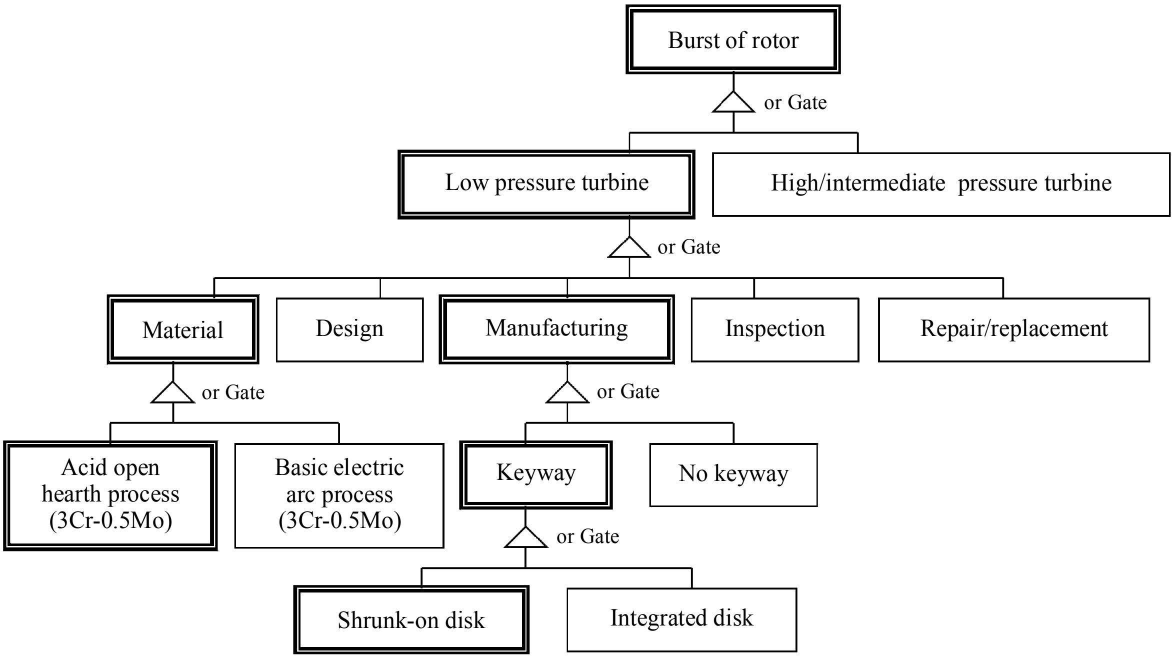

Fig. 5 Fault tree diagram for design and manufacturing errors.

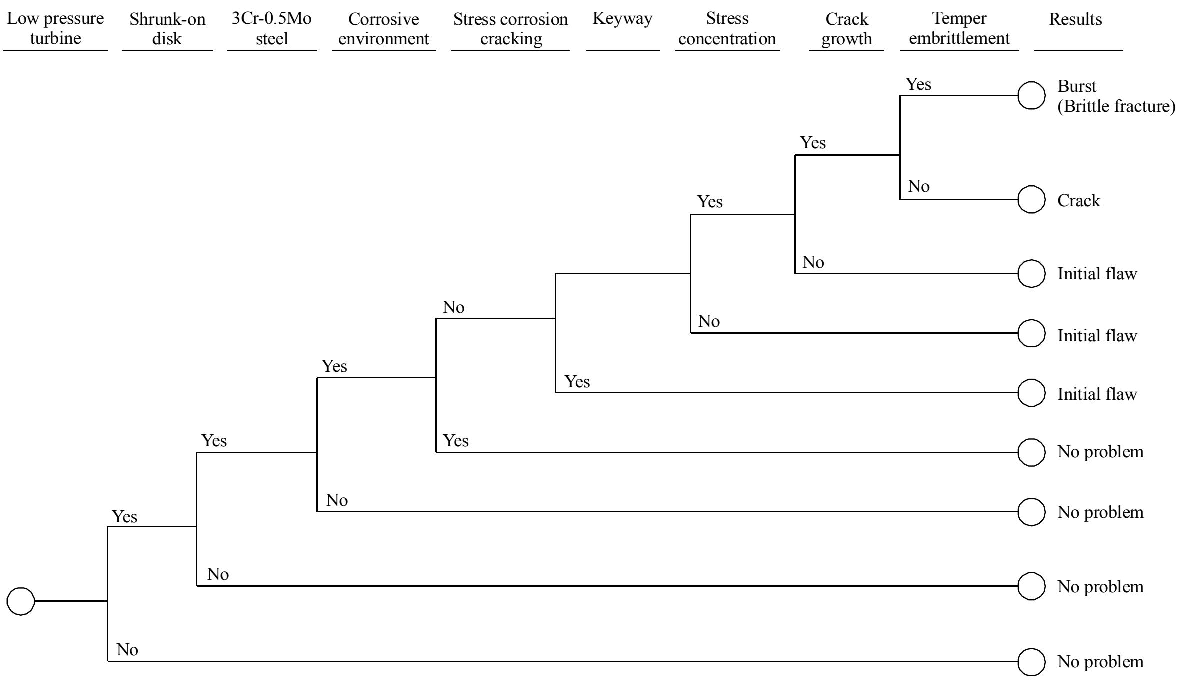

Fig. 6 Event tree diagra m for the low-pressure s team turbine rotor burst at tributed to stress concentration in a shrunk-on disc keyway and the low toughness of a disc material.