Brittle Fracture of Turbine Rotor in Nagasaki

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Engineers were conducting performance and safety tests of a new large-capacity turbine at a shipyard when brittle fracture occurred in the 50-ton rotor, 1,778 mm in diameter (maximum) and 3,590 mm in length, due to microstructural flaws and a strong notch effect. Its fragments scattered in the area surrounding the shipyard, killing 4 and injuring 61 people. This incident happened in the time when larger-capacity turbines were in need for generating more energy to meet the rising demand, and manufacturers were shifting towards fully domestic development instead of joint developments with western countries.

1. Event

Engineers were conducting performance and safety tests of a new large-capacity turbine at a shipyard when brittle fracture occurred at the 50-ton rotor, 1,778 mm in diameter (maximum) and 3,590 mm in length. Its fragments scattered in the area surrounding the shipyard, killing 4 and injuring 61 people.

2. Course

While a traditional turbine had four shafts in three chambers, high pressure with single-shaft, intermediate pressure with single-shaft and low pressure with double-shaft; the new turbine reduced the number of shafts into three, one for the high-intermediate pressure chambers and two in the low pressure chamber as shown in Figure 1.

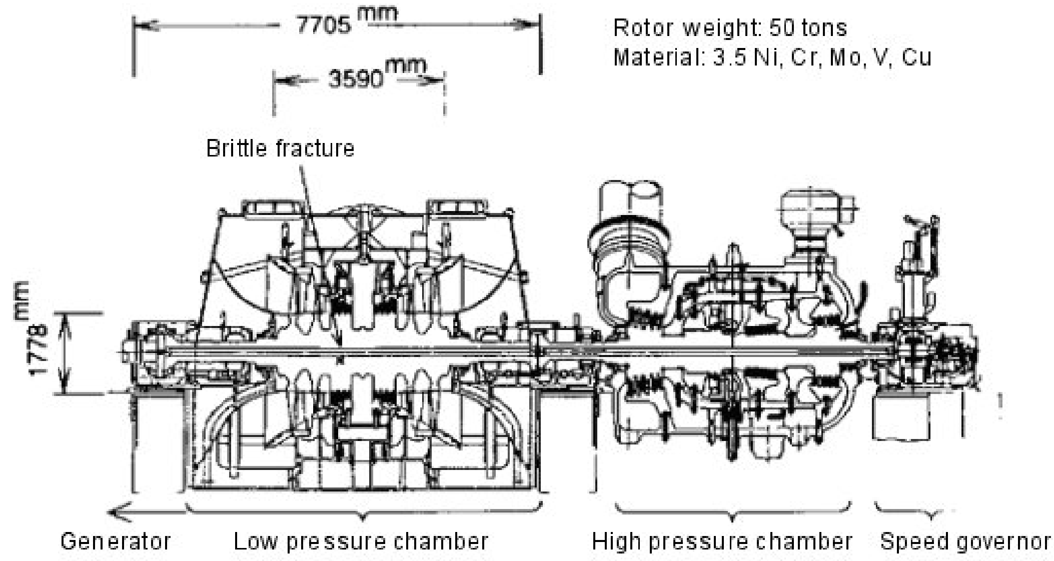

Figure 1. Schematic Diagram of 330,000-Kilowatt Unit [1]

The new turbine also integrated retaining rings at the root of turbine blades connected to the rotor of an electric generator, and the retaining rings became larger in diameter. The high-speed rotor had specially designed rotor blades to obtain high efficiency and increase output.

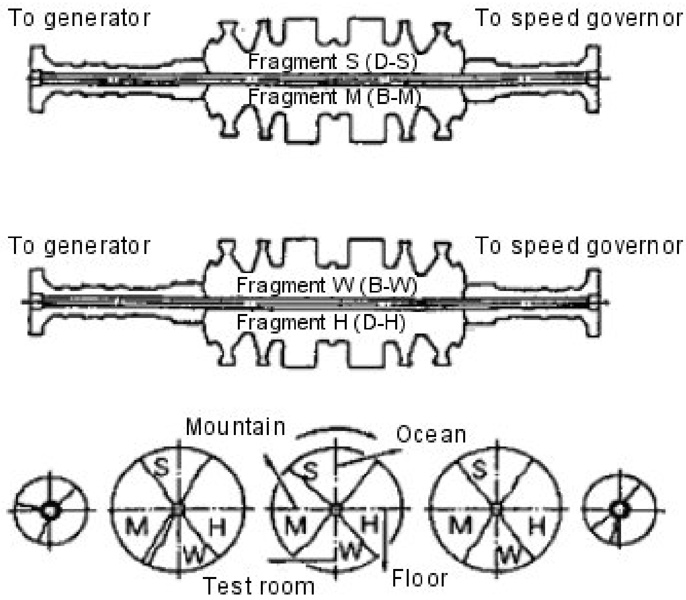

Figure 2. Fractured Turbine Rotor [1]

In order to test the performance and the safety of the assembled new turbine, the rotor drive system was subjected to overspeed runs at 120 percent of the maximum rotational speed. The overspeed test was to increase the turbine speed by 20 % from the normal operation speed of 3,000 rpm to 3,600 rpm.

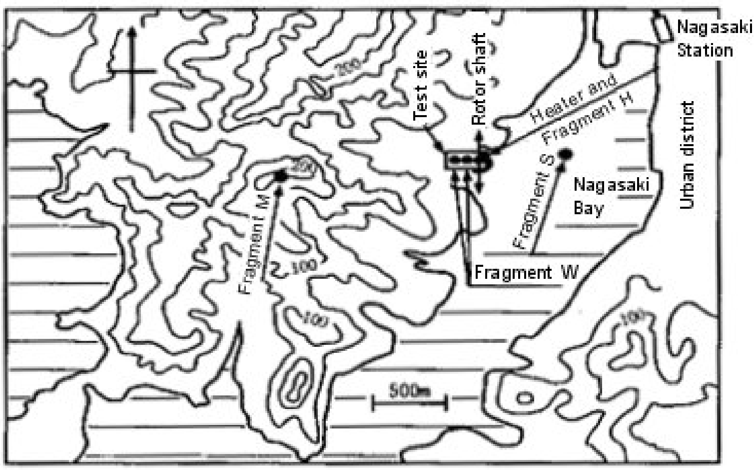

Figure 3. Location of Rotor Fragments [1]

A brittle fracture occurred in the rotor when the turbine speed was increased to 3,540 rpm, 118 percent of the maximum rotational speed. No abnormal blade shaft vibration was monitored during the test prior to the rotor fracture under the test temperature of 40 – 50 degrees C. (The turbine was not subjected to test with high-temperature and pressure steam. The shaft was rotated by a machine.) The fractures started from the rotor bore and broke the rotor into four pieces, almost quadrisectioned (Figure 2). The four rotor fragments was scattered in all directions (Figure 3).

The test site was located at Nagasaki Bay, surrounded by the ocean and mountains. One rotor fragment weighing 9 tons flew 880 meters towards the water (“S” in Figure 3), one weighing 11 tons flew 1500 meters and landed at 200-meter elevation in the mountain (“M”). Two fragments remained in the laboratory - one flew across the test room damaging equipment and injuring people (“W”), and the other struck the floor (“H”).

3. Cause

Photo 1 and Figure 4 show the fracture of the turbine rotor in detail. Failure of the turbine rotor was caused by fractures initiated from a flaw at the rotor bore in the following manner:

(1) The casting of the turbine rotor produced a microstructural flaw such as a pore, crack, or inclusion in the rotor bore. Air and die lubricant were trapped in the cavity, resulted in microporousity in the castings and columnar dendrites across in the bore region of the rotor.

(2) The casting process failed to eliminate the formation of microporousity. The cooling velocity was slow in the rotor bore during the final heat treatment, which caused brittleness in the casting.

(3) The tangential stress increased in the region of the rotor because of the larger rotor size.

(4) Brittle fracture occurred in the rotor bore as the increased turbine speed applied a greater tangential stress to the bore region. Ductile fracture was initiated at high stress points, resulting in the breakup of the rotor.

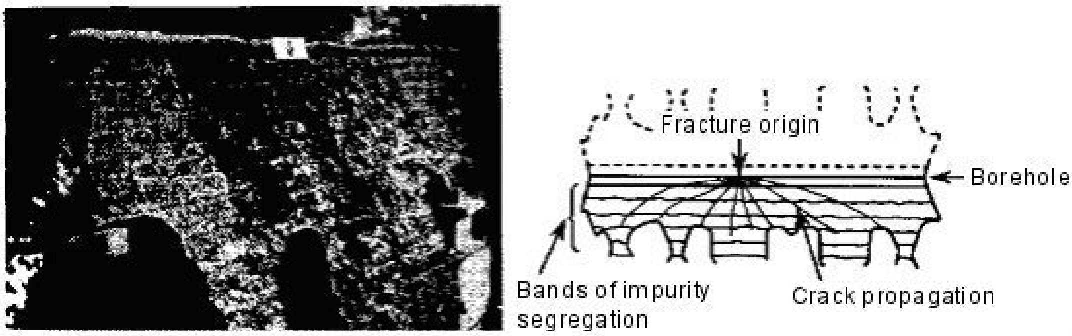

Photo 1. Fracture Origin on the Surface [1]

Engineers failed to understand the microstructural flaws at the rotor bore. It was a possible technical management oversight.

The test used an ultrasonic flaw detector to detect an internal flaw of the rotor. However, it only detected premature flaw echoes (Flaw tolerance: Less than 5 mm in size). It was not proven at time that the collective effect of microporosites in a region is highly destructive to structure, almost equivalent to the destructiveness of a 6 mm flaw. It was still an unknown phenomenon at time related to a microstructural flaw.

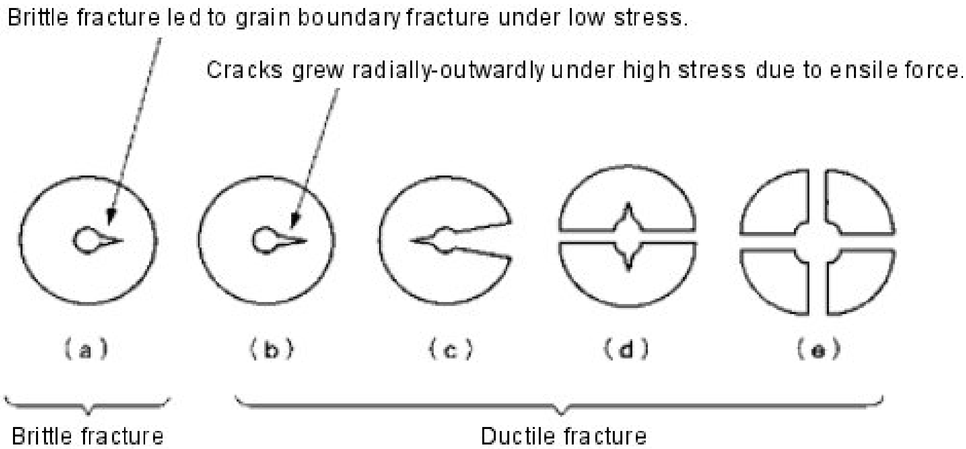

Figure 4. Crack Growth and Rotor Fracture [1]

4. Immediate Action

Engineers investigated what happened, studied the rotor fragments and analyzed the fracture mechanism based on the material properties and the characteristics of the incident. The injured and the families of the dead were well compensated. Details on the incident were centrally controlled so that inaccurate speculation was not circulated in the public. A new turbine was produced using a rotor manufactured by a better casting method, and delivered to the customer in time before the due date that came two months after the incident. No inconvenience was raised to the customer.

5. Countermeasure

The low ductility at the rotor bore resulted in a low tolerance for brittle fracture. In order to eliminate the imperfections and the grain segregation at the rotor bore that caused low ductility, engineers implemented a new casting technology to manufacture the rotor. Instead of the vacuum silicon deoxidation method, they turned to vacuum carbon deoxidation method for producing ingots. In addition to renewing the steel manufacturing process for producing the base material, improvements were made to the heat treatment and the ultrasonic flaw detection methods.

A new spin rig was implemented to prevent recurrence of the accident that resulted in shattering of fragments and casualties. The test equipment and turbine was placed in a pit on the ground and the rotor was covered robustly so that fractured fragments would not scatter in the area.

6. Summary

The turbine failure resulted in a devastating accident with a fractured rotor and many casualties. The incident required many technical improvements, responses to the customer, compensations to the dead and the injured, as well as the social and the legal actions (whether or not to handle the incident as a criminal case and claim professional negligence resulting in deaths and injuries).

7. Knowledge

(1) It is essential to understand all manufacturing processes and related phenomena such as ingot solidification, changes in the crystalline structure during the forging process and in the mechanical properties during forging and heat treatment (embrittlement in particular).

(2) Material properties are not always the same. The same ingredients do not always obtain the same properties.

(3) It is critical to understand the mechanism that leads to a failure. In particular, the fracture mechanism and conditions.

(4) The road to success would be bumpy but worth the effort. The road to success is always under construction, and the road to failure is always smooth. Every measure requires elimination of the root cause to prevent recurrence of the failure. For this incident, the effective measure was implementation of an ingot-making method that does not produce imperfections.

It is also critical to introduce measures for minimizing damage from failures. Such measures require improvements in test equipment and environment as well as drills under hypothetical situations.

8. Background

A turbine is a rotary engine that extracts energy from fluid flow. It is the main mechanical device of a power generation system that extracts thermal energy from pressurized steam by sending steam in high pressure and temperature to the blades attached to a shaft (the rotor assembly). The blades react to the flow so that they rotate and impart energy to the rotor. The generator connected to the turbine convert the energy into electrical energy, which is supplied to communities. Electrical energy is one of the many types of energy that is currently used in the standard operation of human business. The 1970's when the incident occurred were at the end of the high-growth period of the Japanese economy. Low oil prices at time enabled the manufacturers to develop larger turbines for generator systems that can produce more energy and support vital economic activities (The oil crisis in 1973, three yeas after this incident, drastically changed the energy situation in the world). There was also a change in the development trend during 1970's. Domestic development of turbine technology was becoming the industry trend at time, instead of joint development by Japanese and the foreign manufacturers such as Westinghouse (U. S.), General Electric (U.S.) and Siemens (Europe).

References

[1] Yotaro Hatamura (Editor), Jissai-no Sekkei (Practical Design) Research Foundation (1996) *Zoku-Zoku Jissai-no Sekkei (Practical Design III)*, The Nikkan Kogyo Shimbun, LTD.