Latest Technologies and Future Prospects for a New Steam Turbine

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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has completed the actual equipment design of a 1000 MW class tandem compound steam turbine developed in response to recent increasing demand for the enlargement of the capacity of steam turbines. This paper introduces the latest steam turbine technologies applied to this state-of-the-art steam turbine including the complete three-dimensional blade, the low-pressure last stage 50-inch and 60-inch blades, the high performance exhaust hood, the latest sealing technology, the directed lubrication bearing, the advanced 12% Cr steel welded rotor, etc. The current steam conditions are equal to 600°C class USC (Ultra Super Critical), but the practical application of further enhanced steam conditions through 700°C class A-USC (Advanced Ultra Super Critical) is expected. The Ni-based alloy that MHPS developed for A-USC plants is expected to attain the targeted value in strength and underwent a welded rotor for actual-sized rotation tests. Its soundness was verified through a nondestructive inspection. The practical application of A-USC technology will be in view after the long term reliability is verified through a rotation test slated for 2016.

1. Introduction

Since the production of Japan's first land steam turbine (500 kW) in 1908, MHPS's steam turbines have accumulated 341,767 MW of output to date. The reason why steam turbines are still used continuously today is mainly that steam turbines have been supplying stable electric power successfully for years. Other important factors are that the steam conditions have been improving and that steam turbines have been evolving and responding to electric power energy demand by rapidly adopting the latest analysis technologies for their design and applying up-to-date technologies for higher efficiency and reliability to actual products. In recent years, there has been further increasing demand for the expansion of the output capacity of single turbines and improvement in efficiency in terms of environmental concerns. This paper introduces the latest steam turbine development technologies related to capacity expansion and the improvement of efficiency, as well as an overview of the development technologies of A-USC, in which steam conditions are expected to further improve hereafter.

2. Capacity expansion

The steam turbine low-pressure last stage, the output burden of which is large, is one of the most important components in determining the performance, reliability, and overall structure of a turbine. The lengthening of the last stage blades results in the expectation of a reduction in exhaust

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loss and leads to the expansion of the single turbine capacity, contributing to the efficiency enhancement of steam turbines and to a reduction in the number of turbine casings that can make turbine buildings smaller and construction costs lower. At the same time, a turbine last stage can be said to be a compilation of a wide range of technologies extending over materials, performance (fluid), strength, and vibration, and requires very high level technologies and accumulated verification data.

For the drastic improvement of performance and reliability, MHPS adopted an ISB (Integral Shroud Blade) structure where entire circumferential turbine blades are contact-connected with covers, etc., using untwist deformation of the blades in rotating to enhance vibration proof strength. The adoption of this structure also resulted in flexibility in the blade profile shape design, and allowed the development of long blades that can attain further improvement in performance. This long blade development concept started as a part of the development of our high performance new steam turbine[(1)] in the 1990s, and thereafter the performance and reliability of 36-inch blades for 3600 rpm were verified and the development design technology was established in 2003. Moreover, 50-inch blades for 3600 rpm and 60-inch blades for 3000 rpm with further enhanced performance and reliability were developed (**Figure 1**) based on the verification results of the previous technological innovation and the vibration measurement of actual equipment, and application to commercial equipment was completed in 2009[(2)]. **Figure 2** shows the lineup of the high-efficiency and high-reliability steam turbine ISB last stage blades series, and **Figure 3** shows examples of their applicable output ranges.

Figure 1 External view of 50-inch blade for 3600 rpm

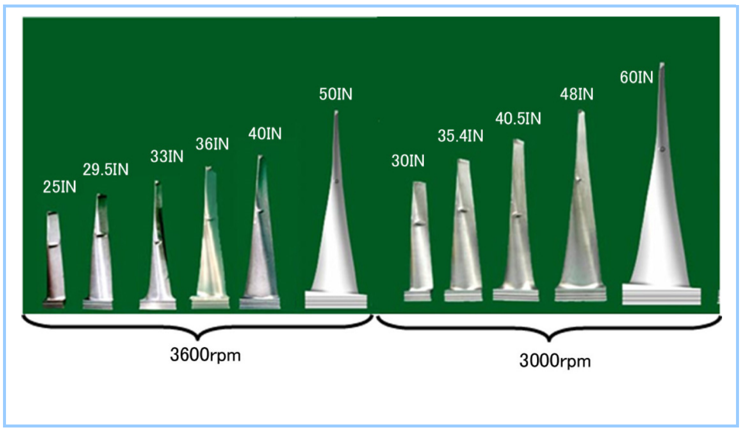
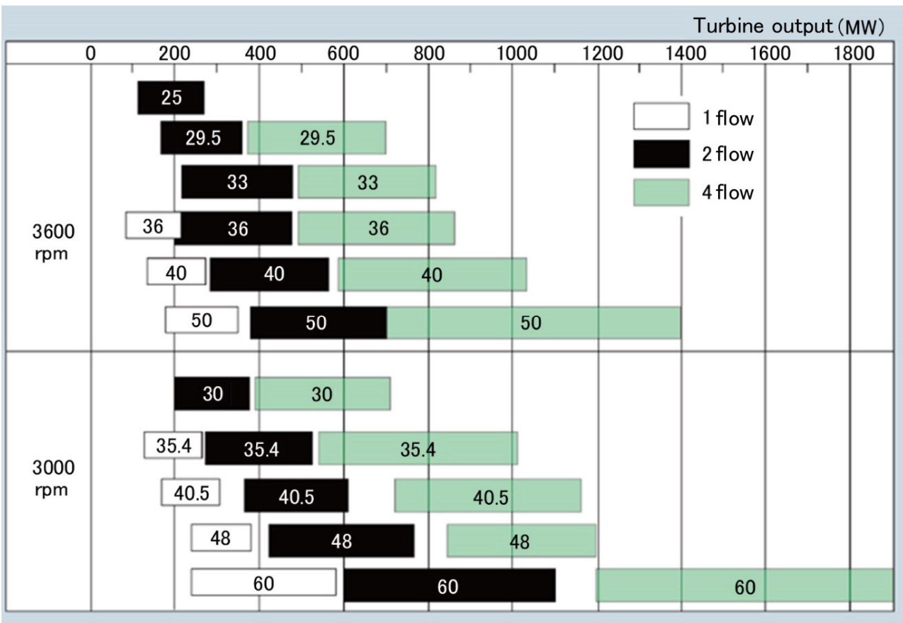


Figure 2 ISB last stage blades series



The numbers in the figures indicate the blade height (Inches).

Figure 3 Application range of ISB last stage blades for 3600 and 3000 rpm

These long blades are applicable to all larger capacities from 100 MW to 1000 MW and higher. In particular, the application of the latest 60-inch blades for 3000 rpm or 50-inch blades for 3600 rpm to 1000 MW class turbines allows significant performance improvement and a reduction in the number of low pressure turbine casings in comparison to existing turbines. In addition, the application of long blades to bottoming steam turbines for gas turbine combined cycle (GTCC) results in considerable benefits. For example, the one-on-one and the two-on-one configuration of MHPS's F and G gas turbines had the low pressure casings for two flows separated from the high and medium pressure casings. On the contrary, the adoption of 50-inch and 60-inch blades allowed a turbine structure consisting of one single-casing reheat turbine (SRT), resulting in the production of a commercially available compact-sized steam turbine as shown in **Figure 4**.

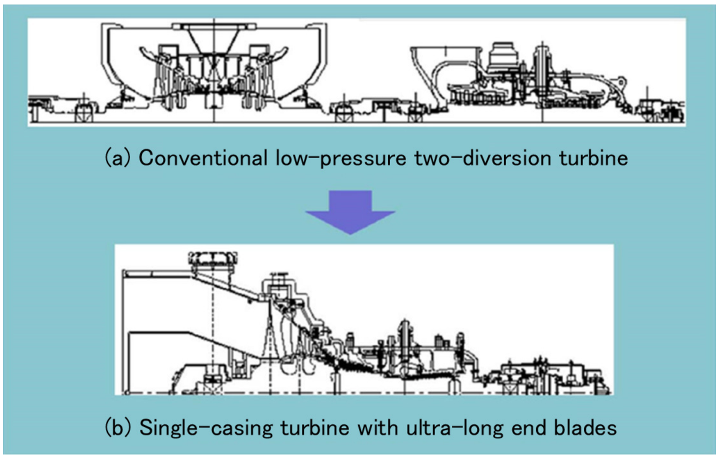


Figure 4 Application example of large GTCC steam turbine

3. Latest technologies for higher efficiency and reliability

The actual equipment design on a 1000 MW class tandem compound steam turbine has been completed. **Figure 5** shows the application points of the latest technologies. These technologies were examined in element technology development and thereafter the performance and reliability were verified through actual load tests.

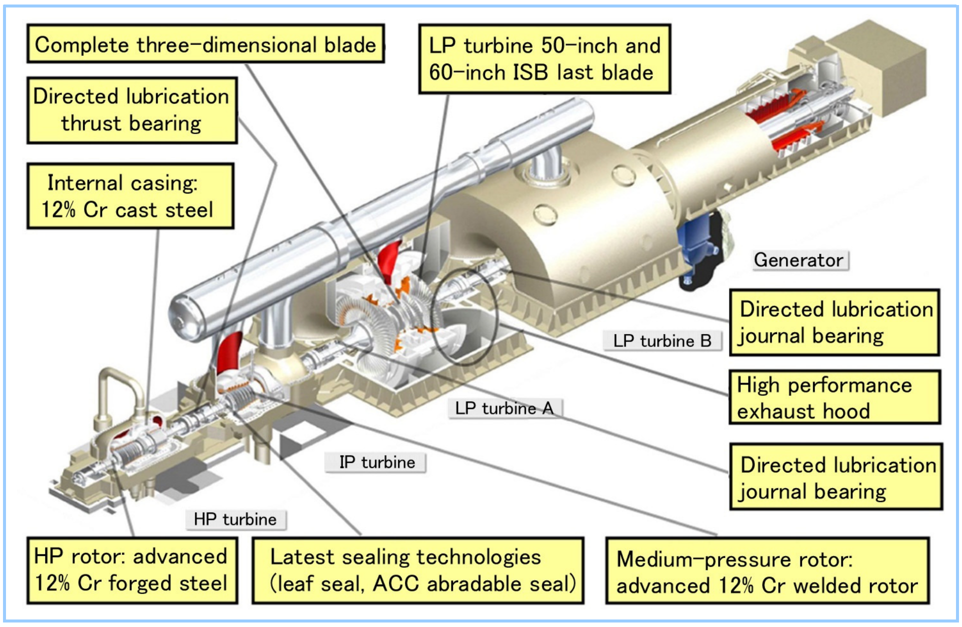


Figure 5 Schematic view of 1000 MW tandem compound steam turbine and applied technologies

(1) Complete three-dimensional blade

For the improvement of the efficiency of blade rows, each stage flow pattern was designed so that the efficiency and output were maximized in consideration of all fluid forces affected by the end-wall contour and the blade profile using three-dimensional multi-stage viscosity unsteady analysis taking into account the non-equilibrium steam properties.

(2) Low-pressure last stage 50-inch and 60-inch long blades and high performance exhaust hood

For the low-pressure L-0 last stage to the L-2 stage where wet steam unique to steam turbines is generated, the position and shape of the water droplet discharge slits are optimized through the prediction of water droplets generated by wet steam. In addition, the flow field from the outlet of 50-inch and 60-inch long blades to the diffuser and the condenser was examined in combination with the blade rows using three-dimensional multi-stage viscosity unsteady analysis taking into account the non-equilibrium steam properties in a manner similar to the analysis of the blade rows. As a result, a new axial diffuser and improved three-dimensional asymmetrical diffuser with a significantly improved pressure recovery coefficient and reduced axial length were developed.

(3) Latest sealing technology

A reduction in leakage loss at the shaft seal is also one of the important performance improvement measures of a steam turbine. As sealing technologies for reducing clearance in rated operation as far as possible, an abradable ACC (Active Clearance Control) seal that allows contact with the fin for minimizing the clearance and a leaf seal that comes into contact with the rotor when the rotor is stopping and becomes non-contact as a result of the slight lift of the leaf tip when the rotor is rotating were developed. An abradable ACC seal reduces clearance in rated operation due to the low-heat generation sealing material with superior sliding characteristics sprayed onto the internal surface of the seal ring as shown in **Figure 6**, and suppresses heat generation from contact with the fin and prevents shaft vibration.

On the other hand, a leaf seal consists of plate-shaped leaves arranged in a circumferential direction as shown in **Figure 7** and becomes non-contact with the rotor only in operation. A leaf seal can be used for sealing points where the pressure difference is larger than the allowable value of a brush seal due to the great axial rigidity resulting from its plate shaped structure. It has been verified using internal verification test facilities that these seals have long-term performance and reliability.

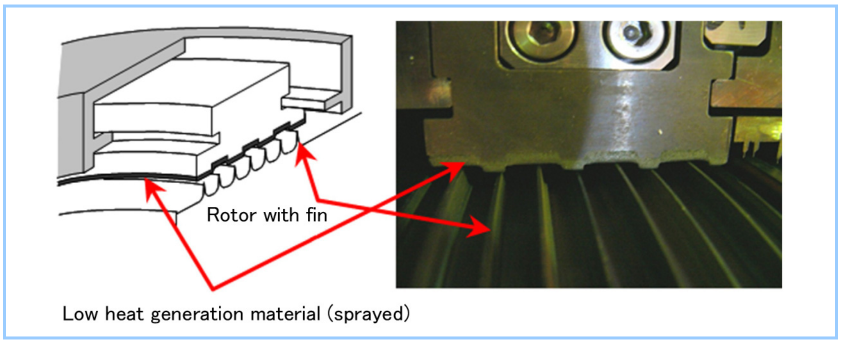


Figure 6 Abradable ACC seal

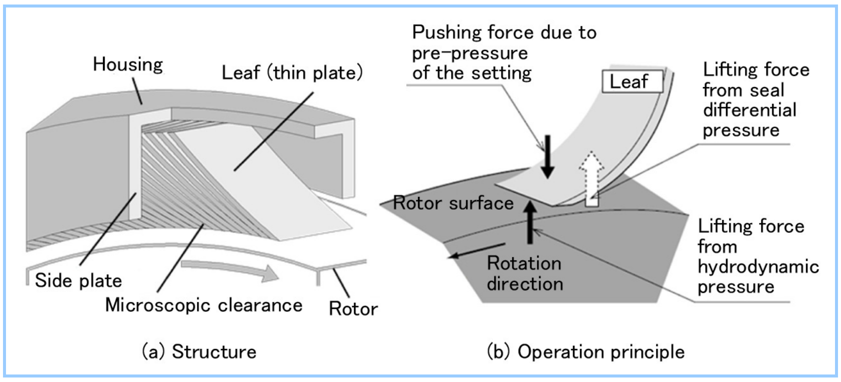


Figure 7 Leaf seal

(4) Directed lubrication bearing

For a reduction in bearing loss, a direct lubrication PEEK (Polyether-Ether-Ketone) bearing that focuses on bearing size reduction is adopted. This bearing uses composite material of PEEK plastic and carbon fiber for bearing sliding parts to attain high surface pressure resistance and has a structure where lubrication oil is directly supplied from the injection nozzle as shown in **Figure 8**, resulting in a lower oil temperature and a significant reduction of bearing loss.

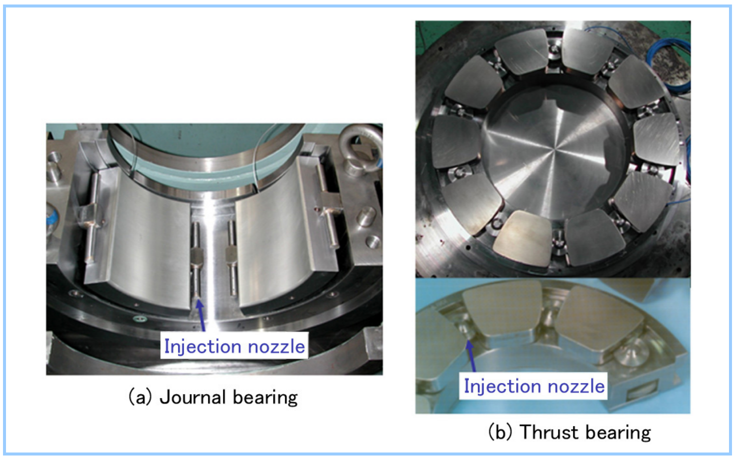


Figure 8 Direct lubrication journal and thrust bearings

(5) Advanced 12% Cr steel welded rotor

The advanced 12% Cr steel welded rotor (MTR10A) that was developed for the over 600°C class USC has been used for commercial machines successfully for more than ten years. At the same time, the practical realization of a welded rotor that can restrict the application scope of expensive high temperature materials including MTR10A to high temperature areas and combine rotor materials suitable for each stage is being carried out. The SRT rotor for GTCC shown in **Figure 9** a dissimilar metal welded rotor that uses MTR10A for the high temperature parts (center) and 2.25% CrMoV steel and 3.5% NiCrMoV steel for the low temperature parts (shaft end). There are no problems with the reliability of a welded rotor even when it is used for GTCC that starts and stops very frequently. Such a welded rotor has been used for for more than twenty actual machines and its sufficient reliability has been verified.

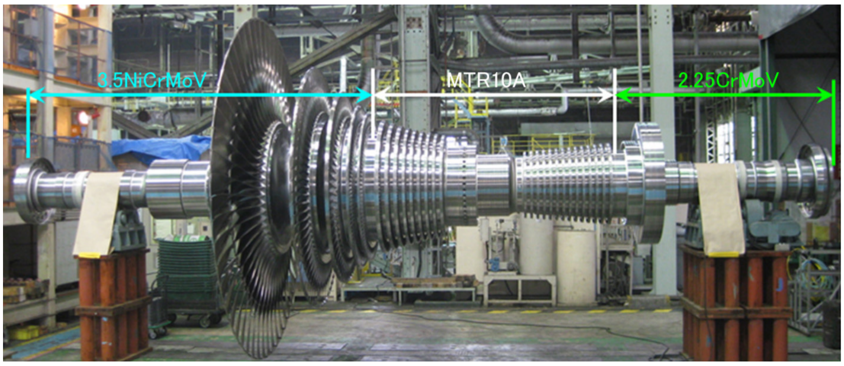


Figure 9 SRT50 welded rotor

4. Improvement of steam conditions (development of A-USC)

Figure 10 shows a history changes in the steam conditions of coal-fired thermal power plants. The steam conditions of coal-fired thermal power plants have changed from subcritical pressure, super critical pressure (SC), and 600°C class ultra super critical pressure (USC) power generation. These steam conditions, which were best suited for the steam turbines of each era, contributed to the improvement of the efficiency of the entire plant together with the adoption of technologies for the improvement of efficiency in steam turbines that evolved according to the times. As a continuation of this improvement of steam conditions, expectations for the practical realization of 700°C class A-USC, the temperature of which is further increased by 100°C in comparison to 600°C class USC, have been raised globally. If A-USC is realized, the turbine efficiency will exceed 50% and a plant efficiency of 46%HHV (higher heating value) or more can be expected. In Japan, a national project for the practical realization of A-USC has been carried out as a subsidized project of the Ministry of Economy, Trade and Industry since 2008. The development issues of A-USC and the development progress are described below.

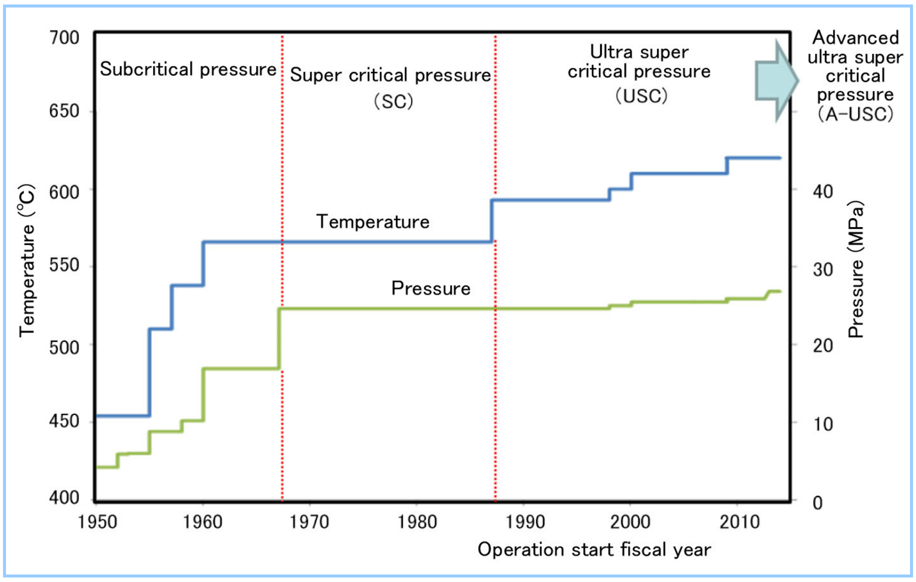


Figure 10　History of changes in steam conditions

4.1　Development issues

The allowable temperature limit for the adoption of current commercially available advanced 12% Cr steel is up to the 630 °C level, and the attainment of even higher steam temperatures requires the use of Ni-based alloy. However, there is an issue with Ni-based alloy characteristics derived from manufacturing in that the structure is highly sensitive to temperature change. Therefore when a larger material is manufactured, there tends to occur a temperature gradient between the surface and the inside, and the problem of segregation, which is uneven concentration distribution of component elements, results. Even if a high strength characteristic is gained with a test piece or small material, it is difficult to attain the strength of a large material that satisfies the objective set by the designer. For this reason, the development of a large Ni-based alloy material that can be used for steam turbine rotors and the verification of its long-term reliability are the most important issues for the development of A-USC. At the same time, it is necessary to design turbine components so that the usage of expensive Ni-based alloy is limited. In particular, it is difficult to manufacture a large forged rotor, and therefore the manufacturing of a Ni-based alloy welded rotor is one of the important development issues.

4.2　Development of new Ni-based alloy

Table 1 shows the Ni-based alloys that we plan to use for practical application. It is estimated that these materials will attain the high-temperature creep strength of more than 100 MPa for 100,000 hours, which was targeted in the national project development. FENIX700 and LTES700R(4) have been used to trial-manufacture a 10-ton class large forged rotor successfully. In addition, these materials used for the trial manufacture of a roughly φ1000 large forged rotor resulted in the nondestructive inspection detection dimension of about 2 mm or less. On the other hand, USC141(5) and USC800 have excellent high-temperature strength and superior hot workability, and they are being verified in many ways for use in blades, bolts, boiler piping, etc. The long-term creep strength of these materials will be continuously tested to 100,000 hours to actually verify the reliability targeted for practical realization.

4.3　High temperature field turbine rotation test

We are now planning to implement a high temperature field rotation test according to the development plan of the national project. This test is intended to confirm the manufacturability of an actual-sized Ni-based alloy turbine and evaluate the remaining life of the post-high temperature field rotation test components in order to verify the reliability.

Based on the trial-designed double reheat steam turbine structure, MHPS deployed, for the turbine used in the rotation test, the following structures: a rotor that includes the same metal welds of the LTES700R and the dissimilar metal welds of the LTES700R and the MTR10A; control stage blades that can withstand variable partial load operation; and the IP sixth stage and IP seventh stage for which the action of centrifugal force is large among dissimilar metal welded components (**Figure 11**).

Table 1 New Ni-based alloys under development and evaluation

Material name	C	Ni	Cr	Mo	Co	W	Nb	Al	Ti	Fe
FENIX700	0.01	42	16	-	-	-	2	1.3	1.7	Bal.
	Iron-nickel-based alloy with a material price that is about two-thirds of that of typical Ni-based alloys. Excellent manufacturability for large forged products. Candidate material for the rotor.									
LTES700R	0.03	Bal.	12	6.2	-	7	-	1.65	0.65	-
	Ni-based alloy with a linear expansion coefficient that is suppressed to approximately the same level as high Cr steel. Excellent weldability. Candidate material for the rotor.									
USC141	0.03	Bal.	20	10	-	-	-	1.2	1.6	-
	High temperature creep strength of about 180 MPa for 100,000 hours at 700°C. Candidate material for the turbine blade, bolt, and boiler heat transfer tube.									
USC800	0.04	Bal.	17	6	23	2	-	4	-	-
	High strength Ni-based alloy with excellent hot forgeability. High temperature creep strength of about 270 MPa for 100,000 hours at 700°C. Candidate material for the turbine blade, bolt, boiler heat transfer tube, and large piping.									

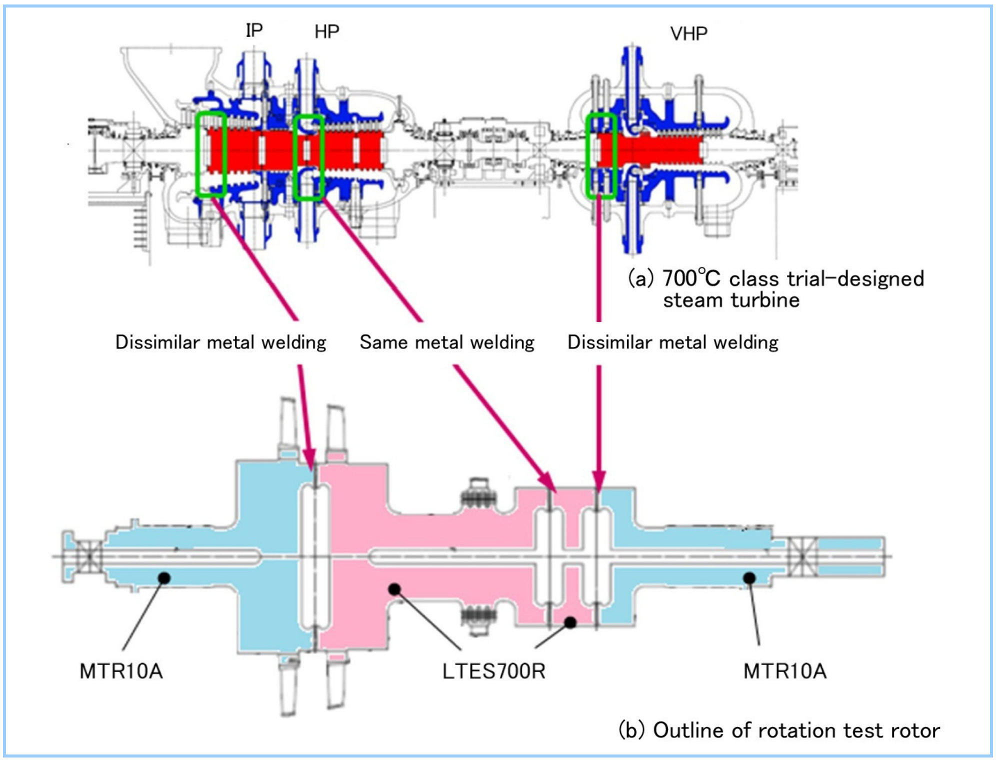


Figure 11 Rotor design concept for rotation test

Figure 12 shows outlines of the turbine rotation test facility and the rotor structure. This facility features the capability of simulating a 700°C or higher temperature field using heat radiated from the heater and a driving motor capable of long-term testing at the rated rotation of 3600 rpm in a vacuum. During this test, the highest stress occurs at the turbine blade root, but it will not be exposed to a temperature as high as 700°C in actual operation. Therefore the life evaluation is an acceleration test against actual operation.

Figure 13 shows an example of a welded rotor, and **Figure 14** shows the nondestructive inspection results of the weld. MHPS had already manufactured welded rotors made of high Cr steel or similar materials and extended the manufacturing technologies to Ni-based alloy. The welding method used was proven TIG welding. We welded an actual-sized mockup, verified the performance of coupling (structure, mechanical characteristics, etc.), and thereafter made a welded rotor for a rotation test. As a result, no problems were found in the nondestructive inspection of the materials and welds and the soundness was verified. In the future, we will manufacture turbine blades that are being developed simultaneously with the welded rotor to complete a rotation test rotor, and implement a verification test in 2016. After the soundness of the material and the welded rotor is verified, we proceed with the practical application of the A-USC technology.

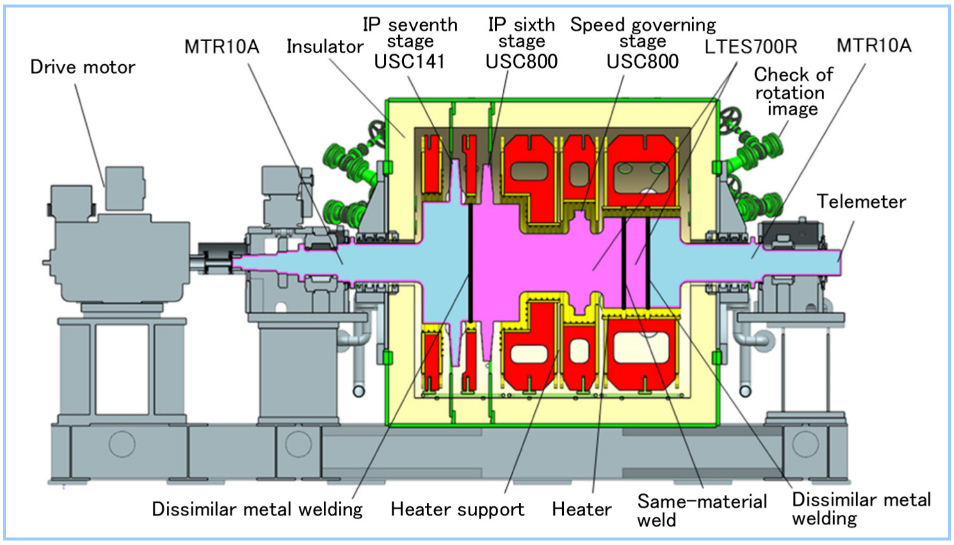


Figure 12 Rotor test facility and structure for rotation test

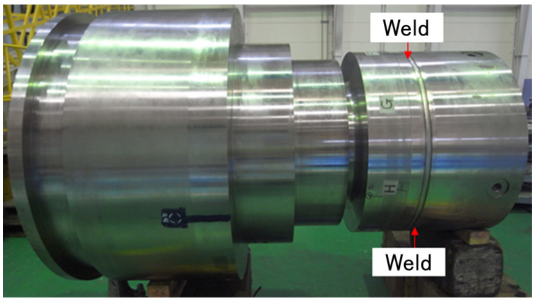


Figure 13 LTES700R welded rotor

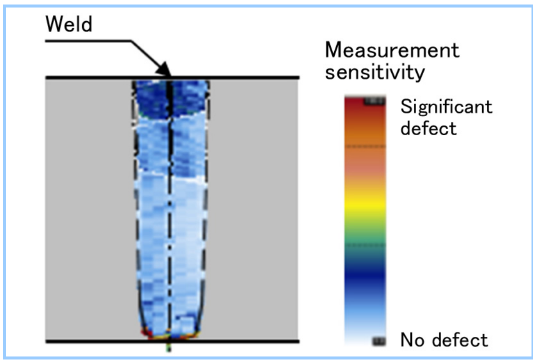


Figure 14 Nondestructive inspection results of weld

5. Conclusion

We have completed the actual equipment design of a 1000 MW class steam turbine that uses 50-inch and 60-inch last stage blades in response to recent increasing demand for the enlargement of capacity. The high-efficiency and high-reliability technologies applied to this designed turbine include the complete three-dimensional blade, the high performance exhaust hood, the latest sealing technology, the directed lubrication bearing, the advanced 12% Cr steel welded rotor, etc. As the practical application of further enhanced steam conditions, 700°C class A-USC is expected, we are proceeding with the element development of a new Ni-based alloy, have started the development of a rotation test rotor, and verified the soundness of the welded rotor through a nondestructive inspection. In the future, the reliability of the materials and the welds will be verified through a rotation test scheduled for 2016.

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