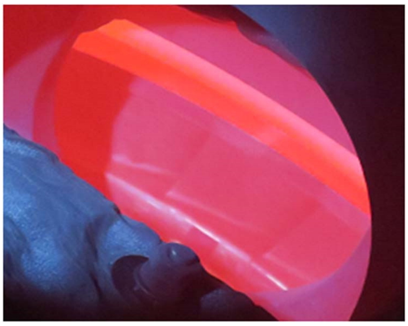
Development of 700°C Class Steam Turbine Technology



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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has carried out the development of the 700°C class A-USC steam turbine through the auspices of a Japanese national project since 2008. We have developed a mainly Ni-based material with a high-temperature creep strength exceeding 100 MPa at 700°C for 100,000 hours with the successful production of a large-scale forged rotor weighing more than 10 tons, as well as fabrication technology for a dissimilar-material welded rotor using the Ni-based material and high Cr steel. We then conducted a full-scale, long-term rotational turbine test to verify these development technologies under test conditions where the steam turbine with a dissimilar-material welded rotor was utilized at a temperature higher than 700°C at 3600 rpm. This paper describes these development technologies.

1. Introduction

Since the production of Japan's first land steam turbine (500 kW) in 1908, MHPS's steam turbines have accumulated over 360 GW of output to date. The main reason why steam turbines continue to be widely used even today is that steam turbines have a proven track record of supplying stable electric power successfully for many years. Other important factors include the fact that the steam conditions have improved and that steam turbines have continued to evolve and respond to electric power energy demand by rapidly adopting the latest analysis technologies in their design and applying up-to-date technologies for higher efficiency and reliability to actual products. In the face of environmental concerns, there has been further increasing demand for the expansion of the output capacity of single turbines and improvement in efficiency in recent years.

Figure 1 lists the historical 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, through super critical pressure (SC), and to 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 have evolved according to the times. As a continuation of this improvement of steam conditions, the need for the practical realization of 700°C class A-USC (Advanced Ultra Super Critical), the temperature of which was further increased by 100°C in comparison with 600°C class USC, has increased globally(1). 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. This efficiency improvement, when converted into fuel cost, can save about 1.6 to 2 billion yen annually in comparison with USC (estimated from the coal price as of January 2017: 60 to 80 dollars per ton(2)), and also contributes to a CO_2 reduction of 25% to 27% in comparison with the global average. In addition, A-USC has the same system configuration as existing coal-fired thermal power plants, so it can be easily used as a replacement for aging thermal power plants. In Japan, a national project for the practical realization of A-USC has been carried out as a subsidized effort of the Ministry of Economy, Trade and Industry since 2008. The development of A-USC is described below.

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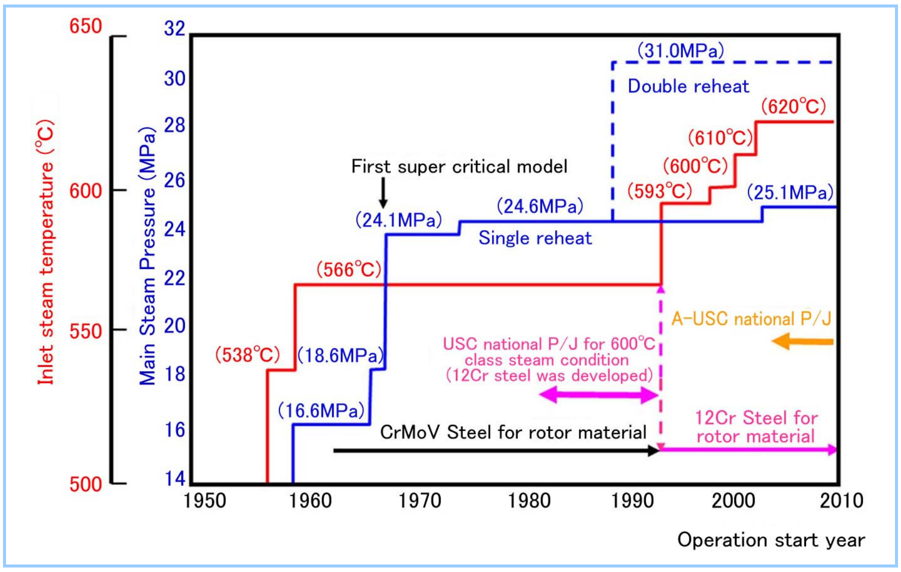


Figure 1 History of changes in steam conditions

2. Issues and schedule of development

The allowable application limit of advanced 12 Cr steel that is currently under consideration for commercialization 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, a temperature gradient tends to occur between the surface and the inside, generating the problem of segregation, which is the uneven concentration and distribution of component elements. Even if a high strength characteristic is gained with a test piece or small amount of material, it is difficult to attain the strength in a large amount of material that satisfies the objective set by the designer. For this reason, the development of a several-ton class 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. In addition, it is necessary to design components so that the use 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.

Figure 2 provides the master schedule of the development[3]. Between 2008 and 2012, materials and element technologies related to boilers, turbines and valves were developed. In order to verify the reliability of the development of these element technologies, actual boiler tests and turbine rotation tests were conducted between 2013 and 2016 for evaluation.

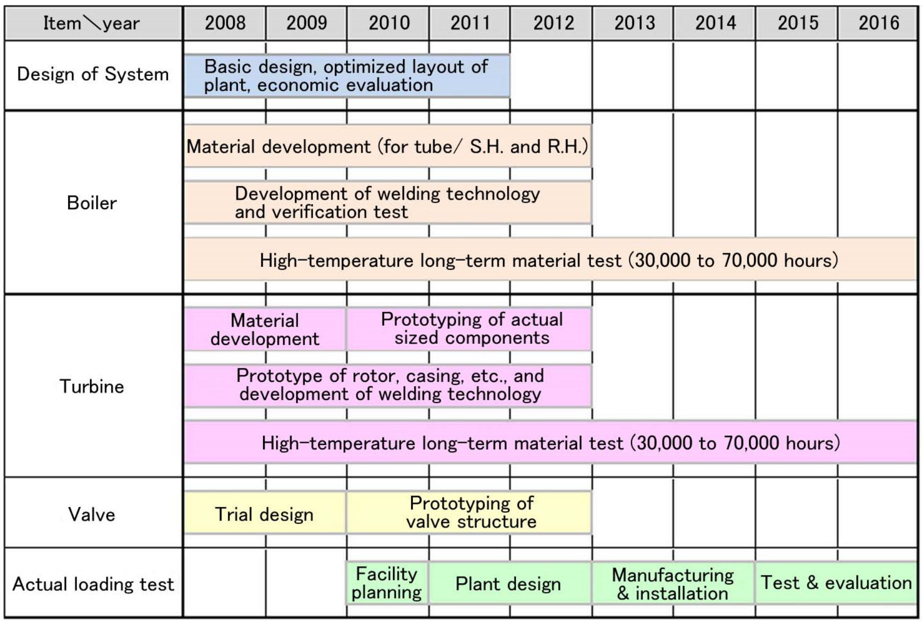


Figure 2 Master Schedule of the A-USC National Project in Japan

3. Development of new Ni-based alloy

Table 1 shows the Ni-based alloys that we developed. It is estimated that these materials will attain a high-temperature creep strength of more than 100 MPa for 100,000 hours, which was targeted in the national project development. FENIX700[4] and LTES700R[5] were used to prototype a 10-ton class large forged rotor successfully. In addition, these materials used for the prototype of a roughly φ1,000 large forged rotor resulted in the nondestructive inspection detection dimension of about 2 mm or less. In addition, USC141[6] and USC800[7] have excellent high-temperature strength and superior workability, and they are expected to be applied in not only blades and bolts, but also boiler piping, etc. The long-term creep strength of each of these materials will actually be tested for more than 100,000 hours continuously, so the long-term reliability is under verification. In addition, the material and mechanical characteristics required for turbine design were obtained and reflected in the turbine rotor design for rotation tests.

Table 1 New Ni-based Superalloys

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 class. 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.									

4. Development of manufacturing technology

4.1 Prototype of welded rotor

Because of the manufacturing limitations of Ni-based alloy forged rotors and to reduce the cost, technology for manufacturing dissimilar-material welded rotors using Ni-based alloy and Cr steel is one the key technologies for realizing A-USC. **Figure 3** is an example of a welded rotor. MHPS has 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.

On the other hand, nondestructive inspection is critical technology to perform reliability inspection of the manufactured welded rotor. The supersonic wave permeability of the Ni-based alloy is inferior to steel. However, the grain size of LTES700R is fine, and its MDDS (Minimum Detectable Defect Size) is 2 or smaller. In addition, we evaluated the supersonic wave permeation property of the weld and developed a sensor which reduced the scattered wave noise of the welding border. Figure 3 indicates the nondestructive inspection results of the weld. No problems were found in the nondestructive inspection of the materials and welds and their soundness was verified.

4.2 Manufacturing

Turbine blade and rotor blade groove structures are complicated and their working tolerances in assembly and manufacturing are severe. To keep working tolerances similar to the conventional levels in cutting difficult-to-cut materials such as Ni-based alloy, it is necessary to improve the manufacturing technology. **Table 2** shows the cutting of a forged blade as an example of the turbine manufacturing process. The Ni-based alloy is a difficult-to-cut material with hard and viscous properties, and since the heat conductivity is low and the cutting heat is concentrated in one place while cutting, there is a problem that local tool damage occurs remarkably early in the process. At the early phase of manufacturing, we had difficulty in selecting tool tips and managing cutting oil. Currently, these problems have been overcome and processing accuracy similar to that of conventional manufacturing can be obtained.

We also planned a control stage blade that can realize partial load operation on the rotation test rotor. In recent years, since renewable energy is often adopted, despite achieving performance improvements in A-USC, we thought that we should consider partial load operation as well. **Figure 4** shows an example of the manufacture of a control stage blade. MHPS's control stage blade consists of three integrated blades and the blade root has a fork structure, which is the most difficult and complicated structure in manufacturing. Therefore, the prototyping of this speed-adjustable blade structure has greatly contributed to the improvement of manufacturing, processing, and assembling technologies for difficult-to-cut materials.

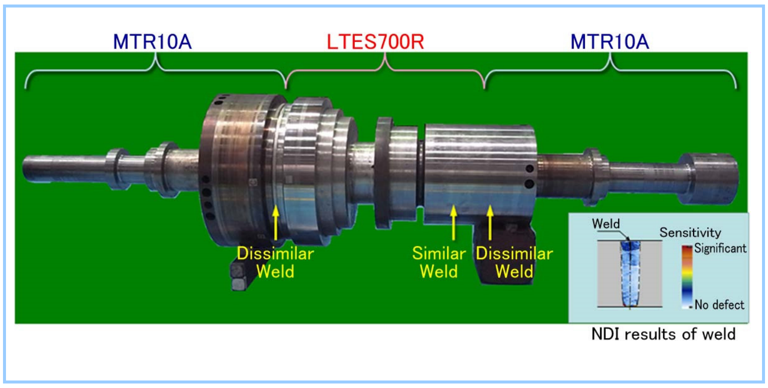
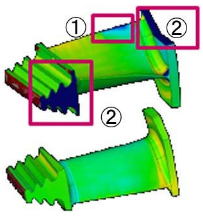
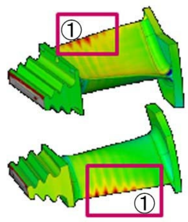
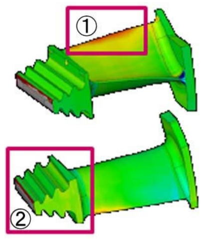
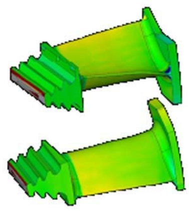


Figure 3 Example of welded rotor application and nondestructive inspection

Figure 4 Manufacturing example of control stage blade

Table 2 Example of forged blade cutting test

No.	#1	#2	#3	#4
Prototyping				
Three-dimensional measurement result				
Point at issue	①A dent on the profile ②Bite into contact part of groove and cover	①Profile surface becomes wavy shape	①Profile end thickness is inappropriate ②Out of tolerance of grove dimension	✓Acceptable level

5. High-temperature field turbine rotation test

We performed a high-temperature field rotation test to verify the reliability of the turbine component. **Figure 5** provides the details of the manufacture and verification of the rotor for the high-temperature field rotation test. This test was intended mainly to confirm the manufacturability of an actual-sized Ni-based alloy turbine and evaluate the remaining life of the high-temperature field rotation-tested components, in particular to verify the reliability of the welded joint part. Based on the trial design of the double reheat steam turbine structure[(3)], MHPS adopted, for the structure of the rotor used in the rotation test, a rotor that includes same-material welded joints of LTES700R and the dissimilar-material welds of LTES700R and MTR10A and simulates the control stage, IP sixth stage, and IP seventh stage where the shape of the blade has relative difficulty in manufacturing (**Figure 6**).

Regarding control stage blades, as described above, it was confirmed that the manufacturability and assembly properties of the complicated blade structure were established with Ni-based alloy. With regard to IP blades, the manufacturability of a forged blade was confirmed. Dissimilar-material welded joints are provided between IP stages assuming adoption on actual equipment.

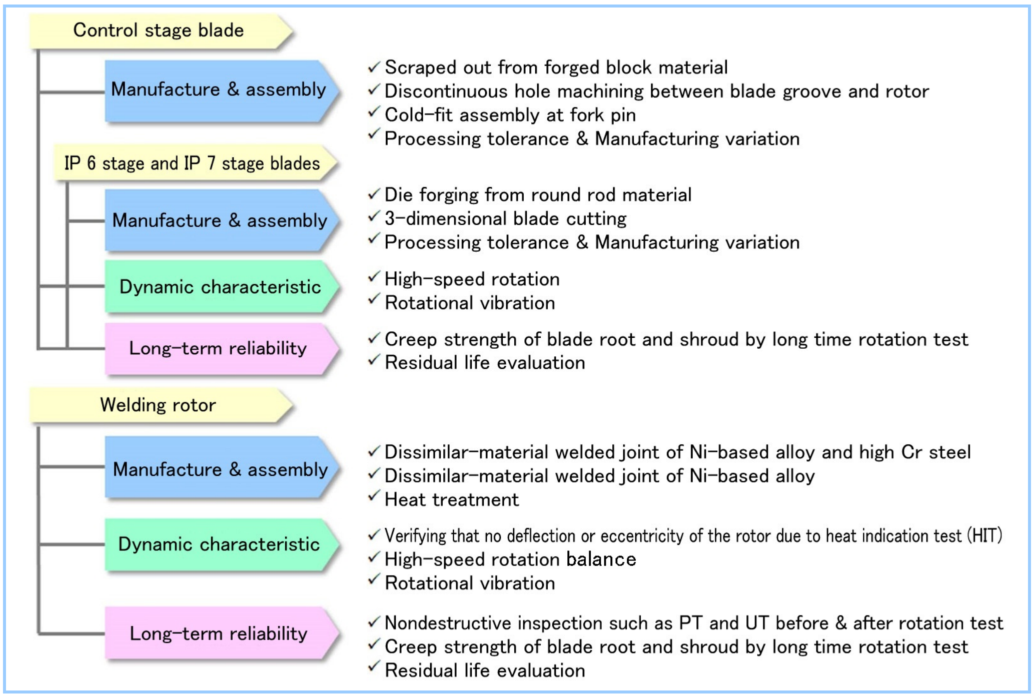


Figure 5　Rotation test verification items

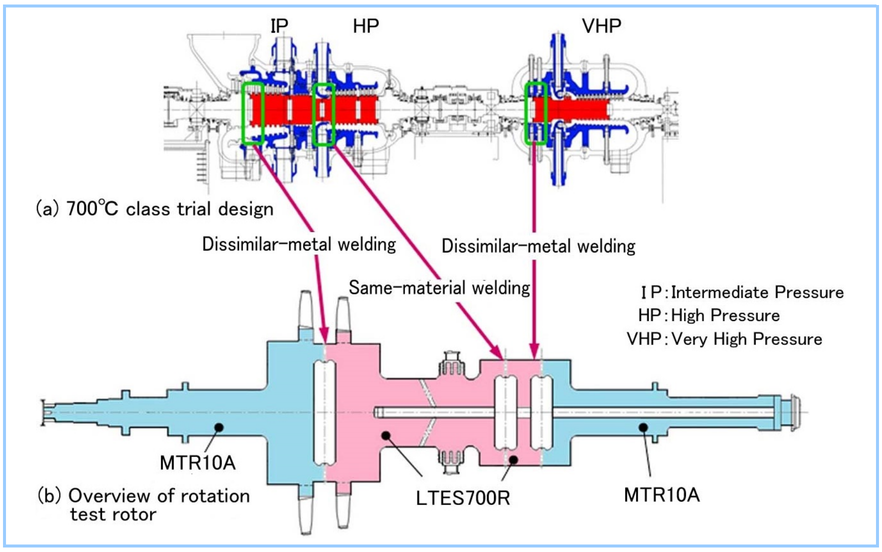


Figure 6　Rotor design concept for rotation test

Figure 7 shows the turbine rotation test facility, the rotor structure and the design plan structure. This facility features the capability of simulating a 700°C or higher thermal field using heat radiated from a heater and a driving motor capable of long-term testing at the rated rotation of 3,600 rpm in a vacuum. During this test, the highest stress occurs at the turbine blade groove, but it would not be exposed to a temperature as high as 700°C in actual operation. Therefore, this life evaluation is an acceleration test against actual operation.

Initially, we planned a creep acceleration test of 100,000 hours by conducting a test for 1,500 hours maintaining the ambient temperature of the control stage blade at approximately 730°C. However, because the joint temperature between the IP stage blades increased due to windage, the equipment and rotor were modified and finally the rotation test was carried out for 1,051 hours at a rated speed of 3,600 rpm.

During the rotational test, we monitored shaft vibration, shaft expansion, heater panel ambient temperature, and rotor temperature 24 hours a day. **Figure 8** shows the photographs of the control stage blades during the test and the test rotor. During the rotation test, the control stage and dissimilar-metal welded joint are kept under a 700°C or higher and a roughly 600°C thermal field, respectively. Thus, the dissimilar-metal welded joint and the control stage blade achieved creep damage corresponding to 160,000 hours and 10,000 hours, respectively, in this 1,051-hour continuous rotation test. As a result of having performed visual inspection, nondestructive inspection, and rotor deflection measurement, etc., after the rotation test for a comparison between before and after the test, there were no particular problems and the soundness of the test turbine rotor was confirmed. We disassembled the rotor to extract test specimens and are evaluating the remaining life.

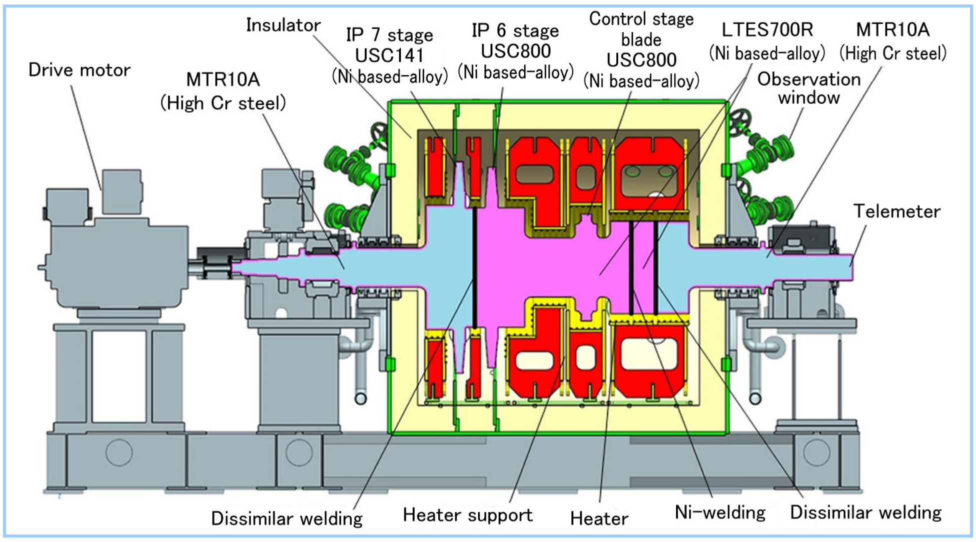
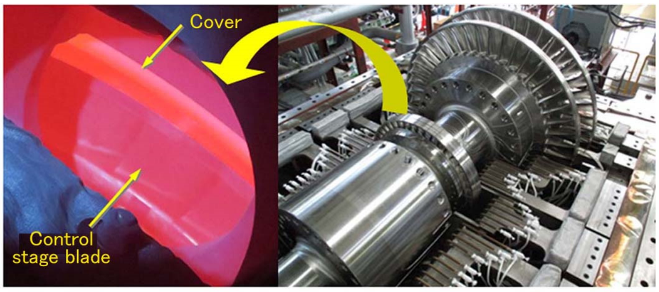


Figure 7 Rotation test rotor and design plan structure



(a) Blades under 700°C at rated speed (b) Test turbine rotor in the facility

Figure 8 Test turbine rotor and control stage blade

6. Conclusion

A-USC turbine development has been going on for nine years since 2008 as a subsidized project of the Ministry of Economy, Trade and Industry and New Energy and Industrial Technology Development Organization (NEDO) and was completed as originally planned. Due to the technology development, prospects for the manufacture of actual 700°C class steam turbines have become clear. At the same time, in addition to the turbine, actual equipment testing of the boiler was also completed. In this actual equipment test, the components experienced 700°C for 13,000 hours. After extubation, test samples were extracted and reliability verification is being carried out. Some creep tests of the materials and the welded joints of both the boiler and the turbine have exceeded 100,000 hours, and the long-term reliability verification is about to be completed. We established the practical application of USC in Japan in the past, and in the same manner, we would like to contribute widely to the world through the practical application of A-USC.

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