

Development of Large-Capacity, Highly Efficient Welded Rotor for Steam Turbines

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Steam turbine plants face increasingly strict market demand for high-temperature operation, streamlining, and short end delivery times. It is thus imperative that a welded-rotor meeting these requirements be developed. The welded rotor operates at high temperature and enables streamlining by using the material for most appropriate high- to low-pressure parts. The use of smaller materials will also enable a shift to larger capacity and shorter delivery time. Mitsubishi Heavy Industries, Ltd., used welded rotors at its Takasago combined-cycle plant (steam turbine output: 105 MW, main steam temperature: 566°C). The firm has been executing proving operations for a common steel welded rotor since March 1997 and a dissimilar steel welded rotor since April 1999. We introduce verification of work execution, strength, thermal stability, and inspection for the welded rotor and actual machine operation under fine conditions.

1. Introduction

Generally, 12% Cr steel and low-alloy steels are used to manufacture rotors for steam turbine plants. For high- to low-pressure integral steam turbines that need to show sufficient strength at elevated temperatures, integral forged rotors made of high-temperature-resistant material (12% Cr steel) are often chosen. Use of 12% Cr steel on the high-pressure side is necessary by reason of its superiority in high-temperature strength, while use of low-alloy steels on the intermediate- and low-pressure sides is preferable because of their superiority in toughness when compared to 12% Cr steel. Mitsubishi Heavy Industries, Ltd. (MHI) has made it possible to manufacture dissimilar steel welded rotors by development of a dissimilar steel welding technique to join 12% Cr steel and low-alloy steel, as well as a common steel welding technique.

Large-capacity, low-alloy steel rotors are conventionally made from large forged parts whose manufacture requires a relatively long period of time. However, welding together of small pieces of forged parts instead of using a large forged part results in increased capacity of rotors and shorter delivery time. For this purpose, MHI has also developed a common steel welding technique for joining together of low alloy steels to permit manufacture of low-alloy low-pressure rotors.

This paper describes welding procedures for manufacture of welded-structure rotors, verified results of strength, heat stability and some other related properties and the actual condition of a welded rotor under operation in a steam turbine.

2. Construction of welded rotor

Among various types of steam turbine rotors

ranging from high- to low-pressure applications, welded rotors designed for high-temperature operation, large capacity and shorter delivery time are outlined in **Fig. 1** (a).

Construction of welded rotors allows use of the materials best suited to particular operating-temperature zones and gives the following advantages. In construction of high- to low-pressure rotors, 12% Cr steel is used in the high-temperature zone because of its high-temperature strength, and 3.5 NiCrMoV steel in the low-temperature zone because of its toughness. Reliability of the entire rotor is thus enhanced by selective use of such steel materials.

In construction of high- to intermediate-pressure rotors, use of 12% Cr steel only in the high-temperature zone makes it possible to increase the rotor capacity and reduce delivery time while maintaining a performance equivalent to or higher than that of integral forged rotors. In the case of low-pressure rotors for operation in the low temperature zone, use of small-size parts made of 3.5 NiCrMoV steel makes it possible to reduce delivery time.

3. Outline of dissimilar steel welded rotor installed in Takasago Combined-cycle Plant for verification of performance

To verify the performance of welded structures planned to be employed for high- to intermediate- and to low-pressure, high- to intermediate-pressure and low-pressure rotors on the operation side of the Takasago Combined-cycle Plant ("T-Plant"), a dissimilar steel welded rotor composed of 12% Cr steel⁽¹⁾ and low-alloy steels (2-1/4 CrMoV steel⁽²⁾ and 3.5 NiCrMoV steel) has been manufactured. As shown

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in Fig. 1 (b), the middle portion of the rotor to be exposed to the highest temperature environment is made of 12% Cr steel, and the end portions are of low-alloy steels, respectively. It thus includes welded joints in three places: dissimilar steel welding to join 12% Cr steel to 2-1/4 CrMoV steel and 12% Cr steel to 3.5 NiCrMoV steel, and common steel welding to join 3.5 NiCrMoV steel parts together. The rotor is about 7.5 m long and has an outside diameter of about 1.5 m and 90 to 120 mm wall thickness of the welded zone.

Integral forged rotors are of either solid or small-bore structure, but welded rotors can be designed to provide large bore provided the wall thickness of the welded joint is sufficient for the load to be applied. Quick start of the steam turbine is needed to keep a high availability rate, but this is not applicable to turbines with integral forged rotors. This is because the rotor is subjected to excessive thermal stresses due to nonlinear temperature gradient in the solid. On the other hand, welded rotors can be started quickly, because they allow large-bore design with a spacious hollow part inside that reduces thermal stresses. To ensure fatigue strength, all welded joints have projections toward the inside to reduce stresses produced on the inside of the welded joint.

In addition, welded joints are positioned in the non-creep temperature zone to prevent the rotor from thermally deforming.

4. Welding of rotors

The temper softening behavior differs greatly in 12% Cr steel and in low-alloy steel. In the case of

dissimilar steel welding, it is difficult to allow the weld heat-affected zones of both steels to be restored simultaneously by a single post-heating treatment. To solve this problem, an appropriate intermediate material was overlay-welded onto the 12% Cr steel portion and a primary post-heating treatment was then applied under conditions suitable for restoration of the weld heat-affected zone of 12% Cr steel. Next, it was joined by welding onto the low-alloy steel portion and a secondary post-heating treatment was applied to the entire rotor under conditions suitable for low-alloy steel. Post-heating treatment was applied by holding the welded rotor in the vertical position to prevent deformation.

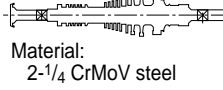
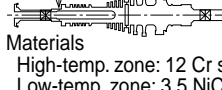
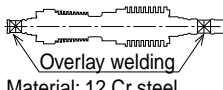
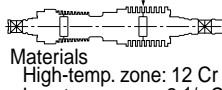
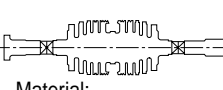
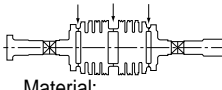
For the intermediate material mentioned above, 9% Cr steel was used to ensure the strength of low-alloy steels having been subjected to the primary and the secondary post-heating treatments.

The 2-1/4 CrMoV steel was used as weld metal for the dissimilar steel welding process, and 3.5 NiCrMoV steel similar to base metals was used in common steel welding of 3.5 NiCrMoV steels, respectively. To prevent loss of strength of the welded joints, V is added to these weld metals in order to suppress the formation of a ferrite band in the weld band.

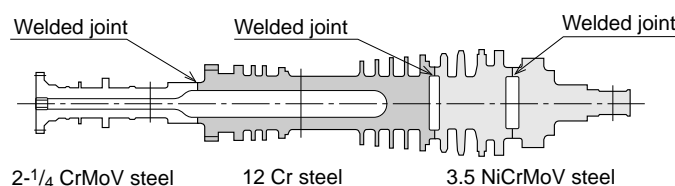
The gas tungsten arc welding (GTAW) method was used both for overlay welding and joint welding of the rotor.

5. Nondestructive inspections

For nondestructive inspections of welded zones after post-heating treatments, the ultrasonic testing method was used as well as surface inspection. For ultrasonic

	Integral forged rotor	Welded rotor	Features of welded rotor
High-, intermediate- to low-pressure rotor	 Material: 2-1/4 CrMoV steel	 Welded joint Materials High-temp. zone: 12 Cr steel Low-temp. zone: 3.5 NiCrMoV steel	Use of 12 Cr steel in high-temperature zone and 3.5 NiCrMoV for zone requiring high toughness results in improved high-temperature performance, large capacity and reduced delivery time. Large bore structure allows quick start operation.
High- to intermediate-pressure rotor	 Overlay welding Material: 12 Cr steel	 Materials High-temp. zone: 12 Cr steel Low-temp. zone: 2-1/4 CrMoV steel	Use of 12 Cr steel only in high-temperature zones results in improved high-temperature performance, increased capacity and reduced delivery time.
Large-size, low-pressure rotor	 Material: 3.5 NiCrMoV steel	 Material: 3.5 NiCrMoV steel	Use of small-size parts results in reduced delivery time.

(a) Shape of welded rotors



(b) Dissimilar steel welded rotor installed in T-Plant

Fig. 1 Welded rotor construction

Table 1 Materials for rotor

	Chemical composition (mass %)									Mechanical properties					
	C	Si	Mn	P	S	Ni	Cr	Mo	V	0.2% yield strength (N/mm ²)	Tensile strength (N/mm ²)	Elongation (%)	Reduction of area (%)	Impact absorption energy at room temp. (J)	Transition temp. (°C)
3.5 NiCrMoV steel	0.26	0.08	0.28	0.004	0.001	3.47	1.73	0.39	0.09	930	1 037	20.0	69.5	166	-130
2-1/4 CrMoV steel	0.24	0.03	0.77	0.006	0.001	0.82	2.21	1.12	0.22	868	989	20.8	66.8	120	-30
12% Cr steel	0.15	0.05	0.60	0.004	0.001	0.63	10.45	1.50	0.16	790	935	20.0	62.1	67	10

testing, both the normal beam technique and the angle beam technique were used to locate imperfections across the entire area of the welded joint. The presence of any imperfections exceeding 1.5 mm is not allowed in order to prevent fatigue crack growth. The ultrasonic tester was set to detect 0.5 mm or larger weld defects. The ultrasonic testing did not detect any harmful defects in the welded joints of the rotor and showed that the welded joints conformed well to the required standard.

6. Performance of welded joints

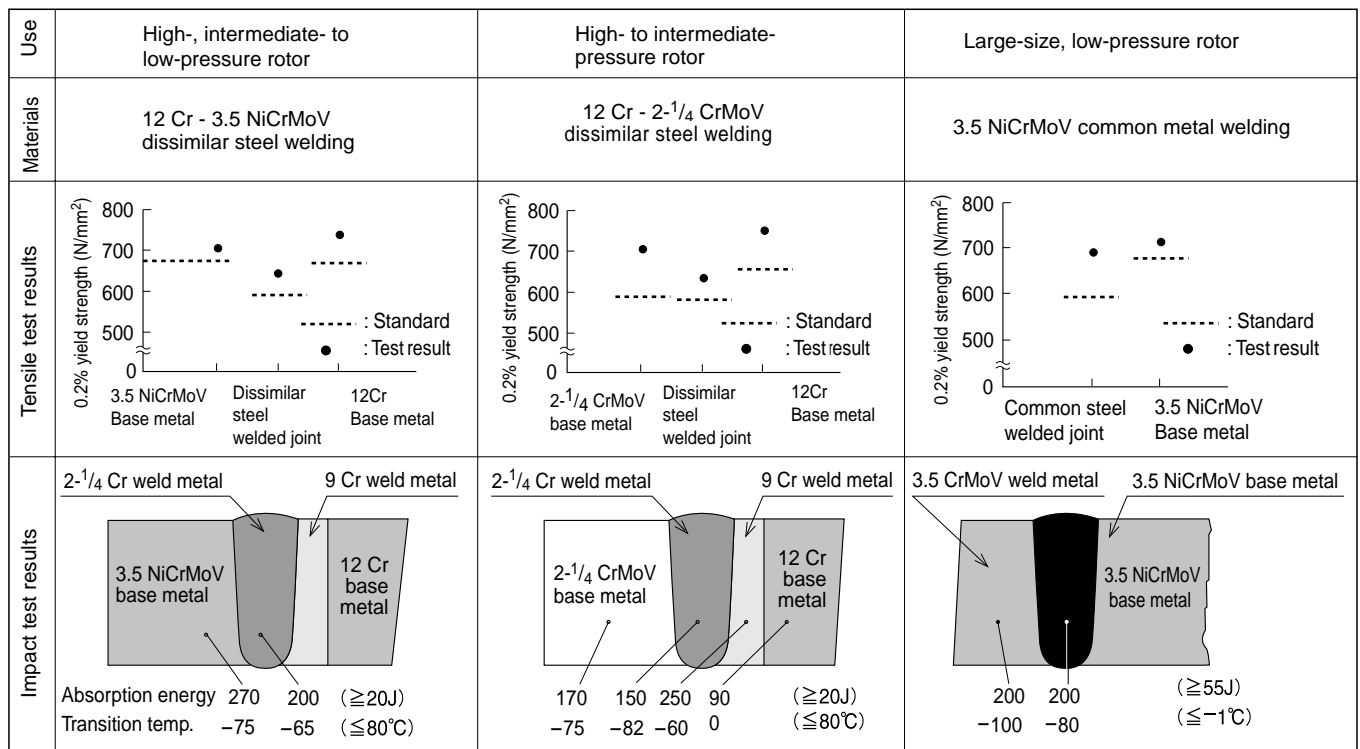
The welded joints composed of steel material equivalent to rotor base metal and weld metal were examined for performance including mechanical properties (Table 1).

6.1 Mechanical properties

The tensile properties (0.2% yield strength) and

impact properties (impact absorption energy at room temperature and 50% fracture appearance transition temperature) of each welded joint are shown in Fig. 2. Favorable results meeting the required standard were obtained from each welded joint. Regarding the impact properties, the welded joints were examined for tendency of embrittlement at the upper limit of operating temperatures in view of secular changes. This demonstrated that the impact properties of the welded zones were equal to or better than those of base metals irrespective of holding time, and that they were substantially stable (Fig. 3).

The welded joints were examined for fatigue strength by the axial-load high-cycle fatigue testing method and also by the low-cycle fatigue testing method using specimens prepared by shaping into actual joints. The test results showed that the fatigue



(Tensile test specimens: O.D 8 mm on parallel portion, gauge length 40 mm)

Fig. 2 Tensile and impact properties of welded joints

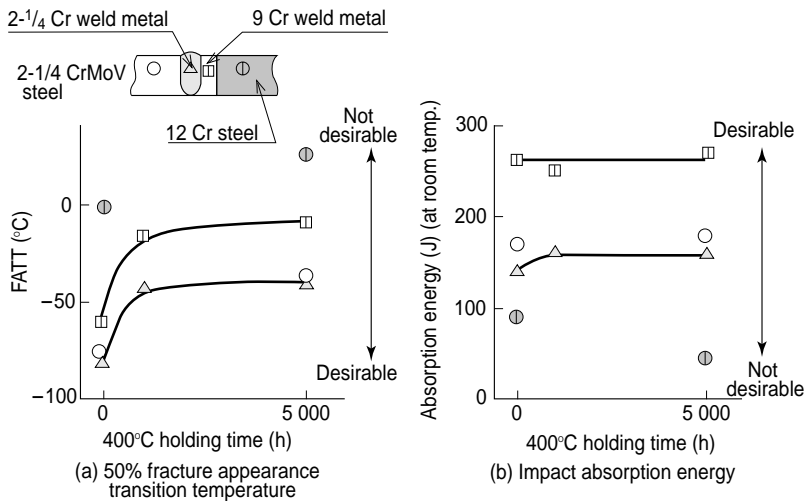


Fig. 3 Influence of long-term heating on impact properties of welded joint
Tendency of embrittlement with long-duration heating is shown.

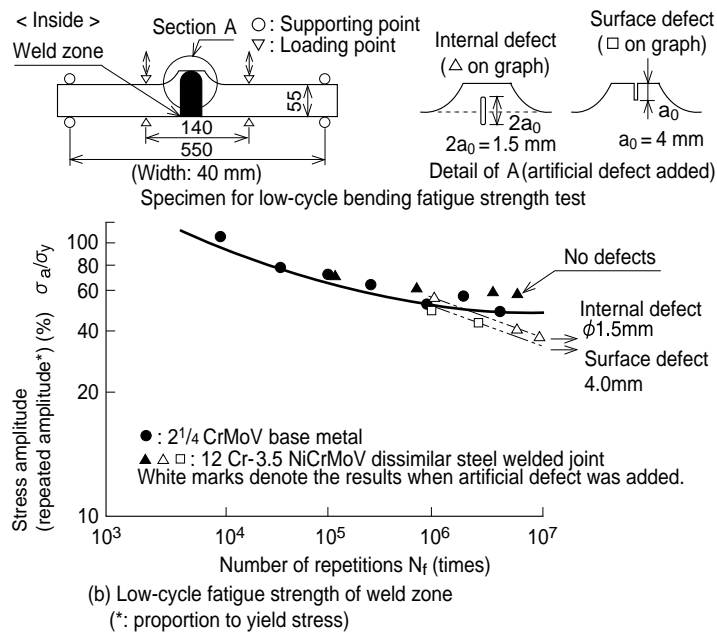
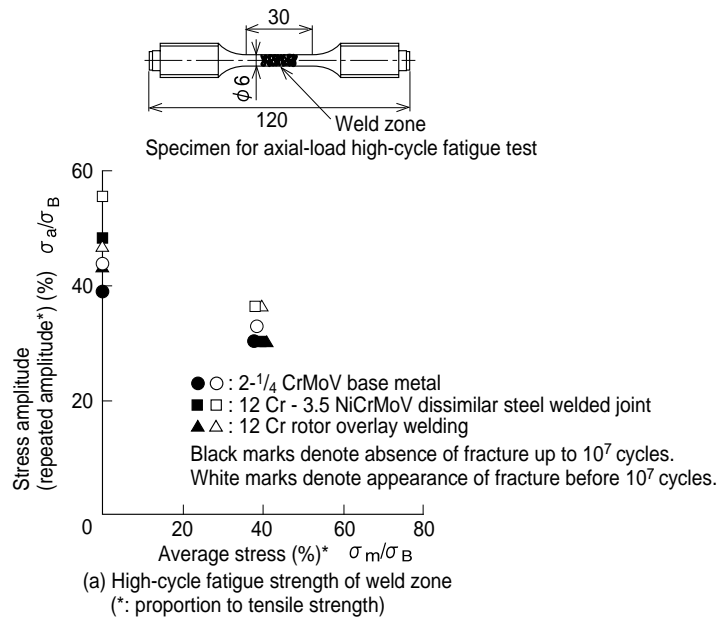


Fig. 4 Fatigue strength of welded joint
Results of high- and low-cycle fatigue strengths of welded joints are shown in contrast to those of base metal.

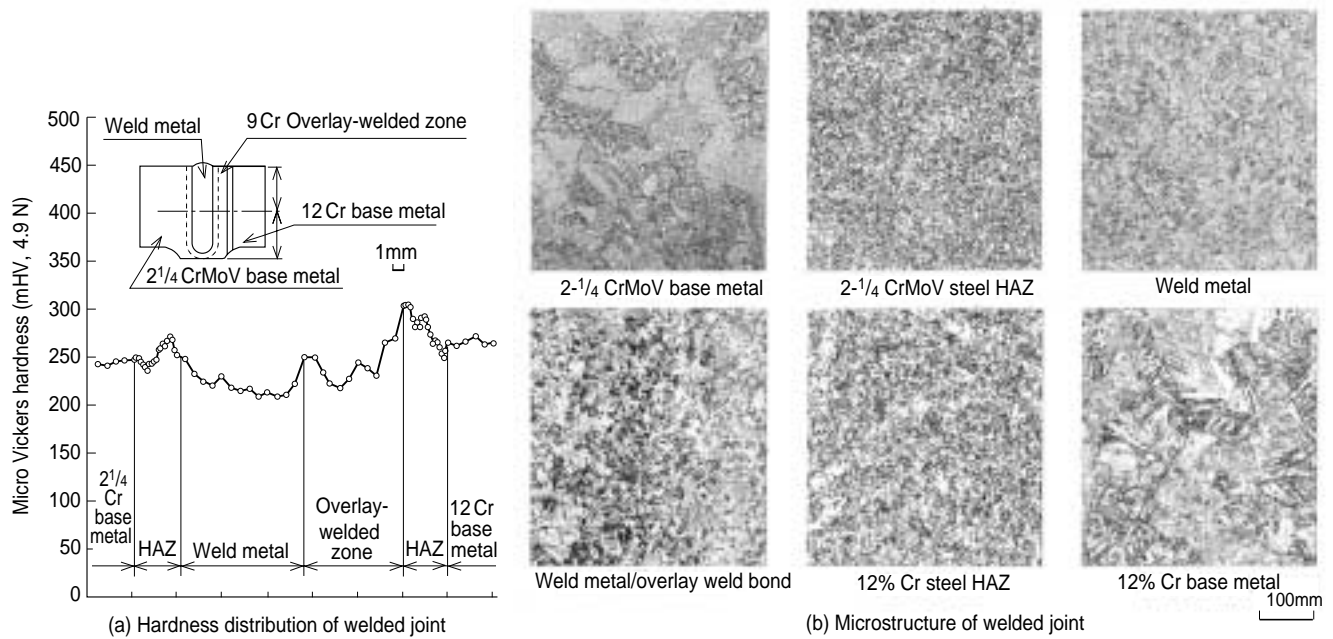


Fig.5 Microstructure and hardness distribution of welded joint

Microstructure of 2-¹/₄ CrMoV and 12% Cr steel welded joint is shown as a typical example of dissimilar steel welded joints.

Table 2 Heat stability test result of dissimilar steel welded rotor

	Measured deflection (Unit: mmP-P)	
	During temperature rise	High-temperature steady state
Measured result	1.5/100	0.5/100
Standard	9/100 or less	4.5/100 or less

strength of all welded joints was equivalent to that of base metals and conformed to the standard required for rotors. The outside surface of welded joints can be machined flat to avoid stress concentration but the inner surface has to be left as welded. Therefore, to ensure fatigue strength, projections were formed on the inner surface of welded joints to reduce stresses produced inside. Fatigue tests demonstrated that the position in which fracture had occurred was at the base of the inward projections (base metal) but not in the welded zone. The influence of artificial defects was also examined, and it was confirmed that they did not affect the performance of the rotor (**Fig. 4**).

The welded joints were also examined for stress corrosion cracking properties under the severest conditions for steam turbine operation (dissolved oxygen concentration: 100 ppb, temperature 130°C, in pure water) and it was confirmed that the properties were equivalent to those of base metals.

6.2 Microstructure and hardness distribution of welded joints

Fig. 5 shows a typical example of microstructure and hardness distribution of dissimilar steel welded joint of 2-¹/₄ CrMoV and 12% Cr steels. No weld defects were found. Both the weld metal and the heat-affected zone exhibited fine grain structure composed of finer

grains than those of base metal and did not include any coarse grain zone that could trigger cracking while being reheated. As the distribution of Cr in welded joints varies greatly between 1.7 and 10.45 mass percent, there may be a risk of forming a ferrite band in the weld band that can reduce the stiffness. However, formation of a ferrite band was suppressed by addition of 0.055 or more mass percent of V to both base and weld metals for fixation of C.

Regarding distribution of hardness over dissimilar steel welded joints, the highest hardness was measured in the heat-affected zone on the 12% Cr steel side. It slightly exceeds hardness HV 300 but is still far below HV 350 around which problem of stress corrosion cracking may arise. Furthermore, the welded joints are located in the dry zone where the temperature does not rise above 200°C to cause stress corrosion cracking. Hence, the hardness distribution of welded joints was confirmed to be favorable.

7. Heat stability of welded rotor

Though steam turbine rotors operate in a high-temperature environment, they are also required to run without deflection despite changes in temperature from ambient to rising temperatures, as well as in a high-temperature steady state. To verify this, deflections of the running rotor were measured

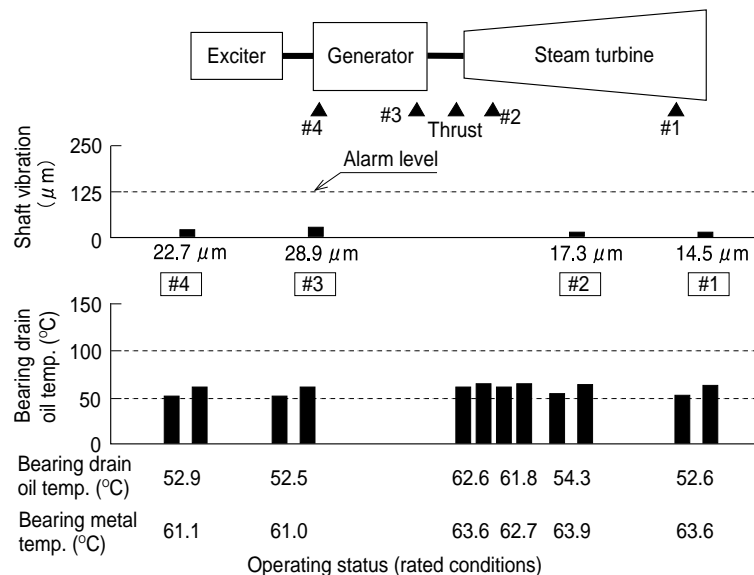


Fig. 6 Actual operation results of dissimilar steels welded rotor
Shaft vibration value in quick start operation is also sufficiently low.

from the time it was started at ambient temperature until the point at which high-temperature steady state was reached. The measurement proved that the deflections of the rotor in both states were on a level with integral forged rotors and met the required standard. The welded rotor was thus verified as being thermally stable (Table 2).

8. Actual performance of welded rotor

The welded rotor is incorporated in a single-casing reheat type turbine of the T-Plant and operated under the conditions of 566°C main steam temperature, 330 MW combined output, and at 3600 rpm with quick start operation. As the first step, a 2-1/4 CrMoV common steel welded rotor was used in the actual operation from March 1997 and demonstrated good performance. Subsequently, operation of the turbine with a dissimilar steel welded rotor was started in April 1999. Fig. 6 shows the measured shaft vibration, temperature of bearing lubricating oil, etc. while the rotor is running in the cold starting and the rated operating conditions. The rotor showed differential expansion value as designed when it was cold started without warming up at intermediate speed, and the shaft vibration value was found to be sufficiently low and steady. Operation of the turbine was also proved sound by the facts that the shaft vibration value during daily operation in the rated conditions was sufficiently low and steady, and that the temperatures of both bearing drain oil and bearing metal were normal.

9. Conclusion

MHI has successfully completed welded-structure turbine rotors to meet recent demands from users for

high-temperature operation, large capacity and short delivery time.

- (1) Welded rotors allow use of the best-suited steel materials for each range of operating temperatures. Development of this technique has made it possible to manufacture highly reliable rotors characterized by both high strength at elevated temperatures and high toughness.
- (2) Because of the difference in tempering characteristics between 12% Cr steel and low-alloy steels, it had been difficult with the conventional dissimilar steel welding technique to join them together in desired ways while maintaining the intrinsic properties of each base metal. The problem was solved by forming an intermediate layer of 9% Cr steel with overlay welding, by applying dual post-heating treatments and by developing new weld metals.
- (3) The ultrasonic testing method can be used in periodical inspections for nondestructive flaw detection.
- (4) In a verification operation conducted at the T-Plant, a dissimilar steel welded rotor including common steel welded joints has been shown to have significant performance in high-temperature operation including quick start operation.

References

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