Application of 12%Cr Steel for Geothermal Turbine Rotor

Yoshikazu Sakanaka

Mitsubishi Heavy Industries, Ltd., Nagasaki, Japan

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Stress corrosion cracking (SCC), 12%Cr steel, weld repair

ABSTRACT

Since the first geothermal turbine was installed at Larderello in Italy, many geothermal power plants have been developed. Due to corrosive gas, impurities and high wetness in geothermal steam, geothermal turbines suffer damage such as high stress part of turbine rotor including moving blades, eroded part of turbine sealing part and last stage long blade and so on. In these a hundred years, so many technologies on material selection, steam cleaning system, low stress designs to prevent the damages have been developed. Today, the reliability of geothermal turbine has been significantly improved and the availability has reached to the level of 90% which is very close to thermal units.

Recently, in order to increase the stress corrosion cracking (SCC) resistance of geothermal turbine rotor materials and improve the reliability of geothermal turbine further, 12%Cr steel has been developed and actually applied for both rotor forging and welding material for refurbishment. In this paper, the result of verification study of 12%Cr steel and the weld repair by 12%Cr steel as welding material for geothermal turbine rotor are introduced.

1. Introduction

Low alloy steels featuring 1%Cr-1%Mo-0.25%V (CrMoV steel) have been used for turbine rotors in geothermal power plants. CrMoV steel is one of the most commonly used and reliable materials for large-scale machine parts such as turbine rotors due to high productivity, high hardenability of the metal matrix, and a good combination of strength and ductility.

In some geothermal power plants which have utilized more corrosive geothermal steam than usual, however, stress corrosion cracking (SCC) of turbine rotors has occurred because of the severe corrosive characteristics of geothermal steam. Changing the steel type from low alloy to 12%Cr is an effective means to increase the SCC resistance of turbine rotor materials[1-2] in such corrosive geothermal steam. Mitsubishi Heavy Industries, Ltd. had already developed 12%Cr rotor steels for fossil-fueled ultra super critical (USC) steam turbines[3-5], and, based on these experiences, we have developed a new 12%Cr steel for use in geothermal turbine rotors.

Furthermore, weld repair procedure for the damage CrMoV steel geothermal turbine rotor in long term operation has been developed. In this weld repair, the damaged part is entirely removed and re-formed by welding of 12%Cr steel which SCC resistance is high compared with CrMoV steel.

In other words, SCC resistance of the weld repaired part is increased, consequently, the reliability of the repaired turbine rotor is improved.

2. 12%Cr Steel Rotor Forging for Geothermal Turbine

2.1 Verification Studies on the Full Size Rotor Forging made of a 12%Cr Steel

A full size turbine rotor forging (23.6 tons in weight) made of a 12%Cr steel was produced, and verification tests on material properties were carried out. No major segregation of alloying elements was observed. Mechanical properties, which were checked at several regions of the rotor forging, satisfy the required values. These results indicate that the 12%Cr steel rotor forging is sufficiently applicable to geothermal power plants.

Figure 1 shows the sampling regions of the verification

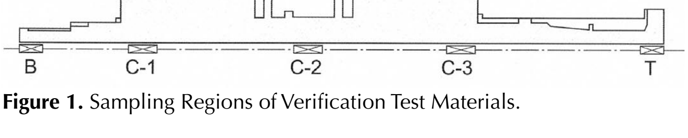

Figure 1. Sampling Regions of Verification Test Materials.

Table 1. Chemical Compositions of Full Size Rotor Forging at Various Regions (mass%).

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	N
X-1	0.04	0.25	0.55	0.009	0.001	0.05	5.10	11.78	1.15	0.03	0.059
X-2	0.04	0.27	0.56	0.011	0.001	0.05	5.15	11.83	1.17	0.03	0.060
X-3	0.04	0.26	0.55	0.010	0.001	0.05	5.08	11.79	1.15	0.03	0.059
B	0.04	0.26	0.55	0.010	0.001	0.05	5.07	11.73	1.15	0.03	0.060
C-1	0.04	0.26	0.56	0.010	0.001	0.05	5.07	11.78	1.16	0.03	0.059
C-2	0.04	0.26	0.55	0.010	0.001	0.05	5.07	11.74	1.13	0.03	0.060
C-3	0.05	0.27	0.57	0.011	0.001	0.05	5.12	11.79	1.16	0.03	0.060
T	0.05	0.27	0.57	0.011	0.002	0.05	5.13	11.88	1.18	0.03	0.059

test materials. Table 1, overleaf, shows the chemical compositions of the full size rotor forging, as ascertained at various regions. Comparison of chemical compositions at each region demonstrates that segregation of alloying elements is very slight. The content of impurity elements (phosphorous, sulfur, etc.) was suppressed to the lowest level possible in industrial production.

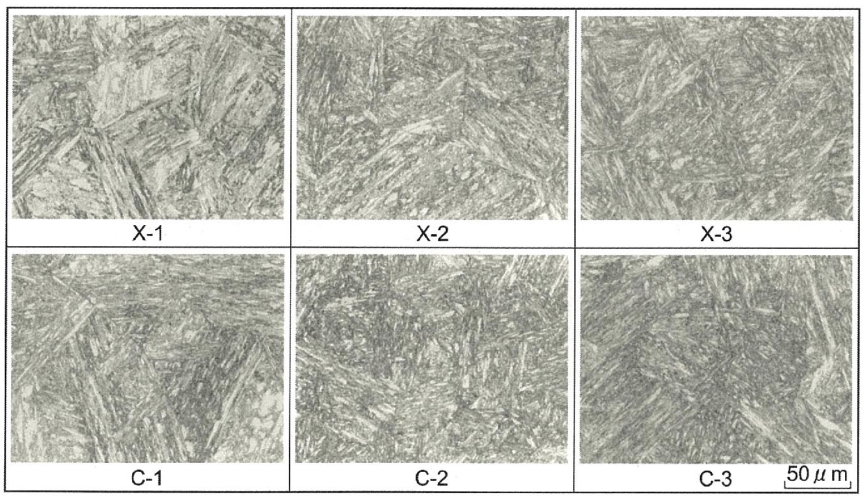

Figure 2. Optical Micrographs of Rotor Forging at Various Regions.

Figure 2 shows optical micrographs of the rotor forging at various locations. The microstructure observed in Figure 2 was tempered martensite containing a considerable amount of austenite. No major differences in microstructure were found among the various locations, nor was the harmful δ-ferrite phase observed, thus indicating a sound microstructure. It should be noted that, because the austenite was in the form of an extremely thin film between the martensite laths, it cannot be discerned in the photograph presented here.

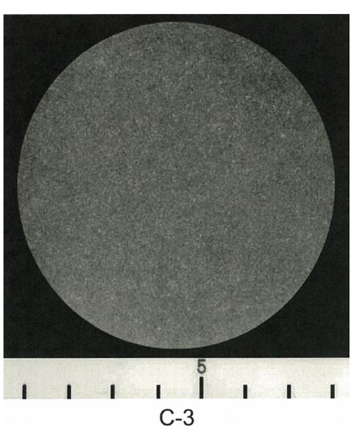

Figure 3. Macro-Structure of the Center Core Bar.

Figure 3 shows the macrostructure of the center core bar. Network segregation and δ-ferrite, which sometimes appear in the center of large scale 12%Cr steel ingots, were not observed in any region.

Table 2 shows the results of tensile and impact testing performed with the materials sampled from several regions of the rotor forging. Both of these properties satisfy the required values. Toughness in particular is so excellent that the FATT (fracture appearance transition temperature) is as low as – (minus) 160°C, which is due to the fact that tough austenite exists in the form of an extremely thin film between the martensite lath. There were no major differences in tensile and impact properties from region to region. Compared with CrMoV steel, 12%Cr steel has almost the same mechanical strength and more excellent toughness.

Figure 4 presents the SCC test results. The CrMoV steel used as the control was subjected to bending stress equivalent to 0.2% proof stress, as well as a sharp notch having a stress concentration factor of 3.3, thus causing SCC to accelerate. Signs of initial crack occurrence were already apparent after holding for 3 months. After the elapse of 6 months, SCC-induced cracking was readily apparent.

In contrast, 12%Cr steel for geothermal use showed no signs of crack initiation even after the elapse of 12 months under severe test conditions. This extremely good SCC resistance is considered to be due to the very fine mixed structure of the martensite lath and austenite. That is, in addition to the presence of a highly anti-corrosive austenite phase, local stress is alleviated by structural fineness and the soft austenite phase, and this is considered to result in the improvement of SCC resistance.

As shown, the full size rotor forging produced in this study features excellent microstructure and mechanical properties sufficient for use in a geothermal power plant and improved SCC resistance.

2.2 Application Experience of 12%Cr Rotor

Recently, 12%Cr rotor has been applied to 3 geothermal turbines in the event of replacement of old turbine rotor with new one. Specification of these 3 geothermal turbine are shown in Table 3.

3. Weld Repair for Geothermal Turbine Rotor Damaged by SCC

For geothermal turbine, there is Wilson Zone, where steam phase changes from vapor to liquid phase due to saturated geothermal steam at turbine inlet. Therefore, more contaminant in geothermal steam accumulates in Wilson Zone compared with other part. In addition, relative high tensile stress oc-

Table 2. Mechanical Properties of thte Full Size Rotor Forging at Various Regions.

	Tensile Testing				Impact Testing	
	0.2% proof stress (MPa)	tensile strength (MPa)	elon-gation (%)	reduc-tion in area (%)	absorbed Impact Energy at 25°C (J)	50% FATT (°C)
Required Value (Specification)	Min. 635	Min. 740	16	45	30	40
X-1	703	905	20.6	52.7	140, 141	-162
X-2	736	894	20.6	54.8	122, 129	-164
X-3	705	909	21.0	53.8	143, 136	-160
C-1	742	892	20.6	52.7	122, 126	-167
C-2	760	894	20.6	52.7	124, 122	-182
C-3	760	905	20.0	51.6	134, 127	-172
Example of CrMoV Steel	679	799	23.2	67.7	189, 199	-40

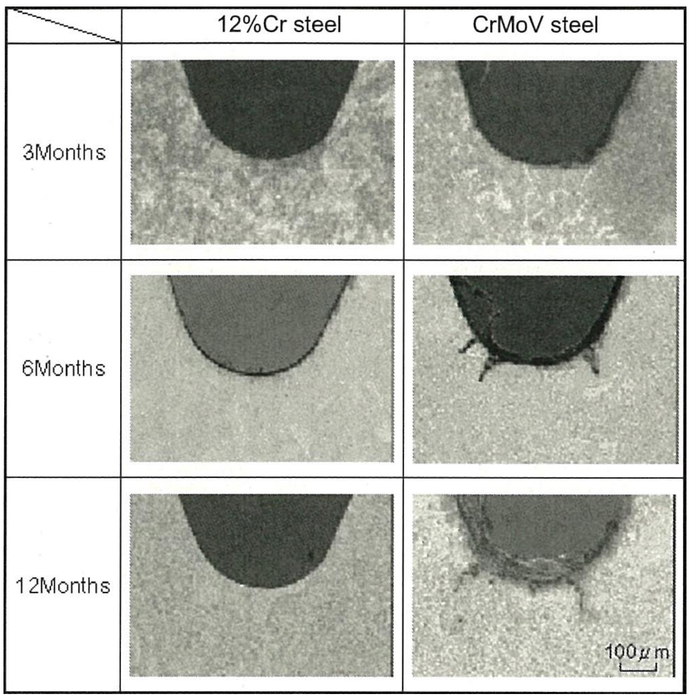

Figure 4. Cross Secrion of SCC Acceleration Test Specimens Taken from the Full Size Rotor Forging (With bending stress equivalent to 0.2% proof stress).

Table 3. Specification of Geothermal Turbine (Application Experience of 12%Cr Rotor)..

Turbine	SC1F-16.5"	SC2F-25"	SC2F-25"
	Single-Cylinder, Single Flow Impulse-Reac-tion Condensing Turbine	Single-Cylinder, Double Flow Impulse-Reac-tion Condensing Turbine	Single-Cylinder, Double Flow Impulse-Reac-tion Condensing Turbine
Rotor Weight	3.5 ton	22.1 ton	22.1 ton

curs at some part of turbine rotor due to centrifugal force etc. Consequently, after the long operation, stress corrosion

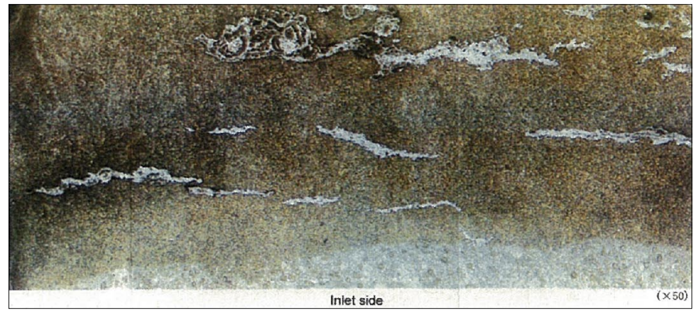

Figure 5. Stress Corrosion Cracking in CrMoV rotor.

cracking (SCC) may occur at such part by a combination of the accumulation of contaminant and relative high tensile stress.

As a result of magnetic particle testing (MT) and Replication, the crack indications are found as shown in Figure 5. In case that the crack is small, the cracks can be removed within the allowable thickness of each part. On the other hand, in case that the crack is large, the cracks can not be removed within the allowable thickness. In such case, the damaged part is entirely removed and re-formed by welding of 12%Cr steel.

Table 4. Chemical Compositions of 12%Cr steel for Weld.

C	Si	Mn	P	S	Cu
0.04	0.26	0.55	0.010	0.001	0.02

Ni	Cr	Mo	V	N
5.09	11.74	1.14	0.03	0.060

Chemical compositions of 12%Cr steel for weld are shown in Table 4 and almost the same as that of 12%Cr steel rotor forging shown in Table 1.

3.1 Verification of Welding Repair by 12%Cr Steel

The tensile test was carried out to verify the strength and the weldability between CrMoV rotor material and 12%Cr steel. The fracture was occurred at not 12%Cr welded material or heat affected zone but CrMoV rotor material as shown in Figure 6. This result proves that 12%Cr welded material and heat affected zone have sufficient and higher strength than the base material. Table 5, overleaf, shows the result of tensile test.

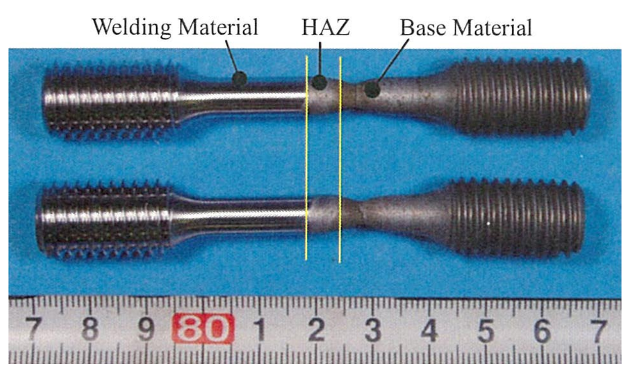

Figure 6. Tensile Test.

It is generally said that the material with high hardness has high susceptibility to SCC.

Hardness of 12%Cr welded material, heat affected zone and CrMoV rotor material zone are measured. As shown in

Table 5. Tensile Test Result (at room temperature).

material	0.2% proof stress (MPa)	tensile strength (MPa)	elonga-tion (%)	reduc-tion in area (%)
base material(CrMoV steel) specification	Min. 635	Min. 740	16	45
heat affected zone	672	810	18.0	65.6
welding material 12%Cr steel	820	922	20.4	66.6

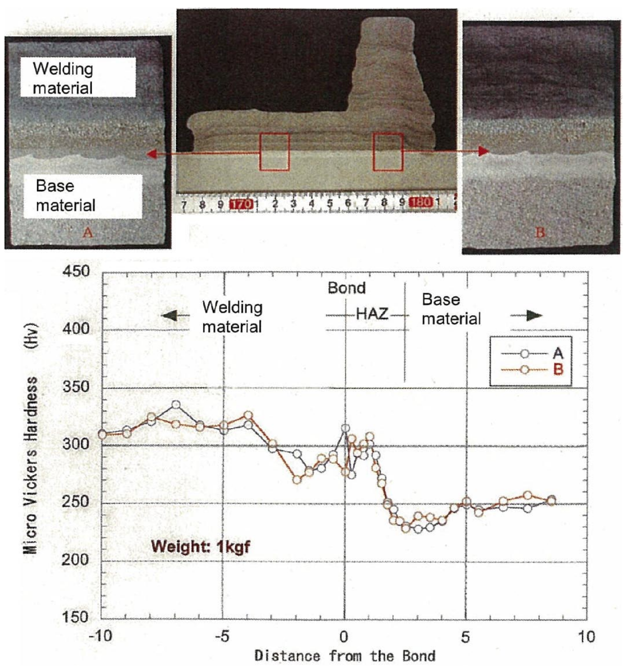

Figure 7. Measuring Result of Hardness.

Figure 7, overleaf, the hardness is low enough due to appropriate stress relief heat treatment (SR).

3.2 Application Experience of Weld Repair by 12%Cr Steel for Geothermal Turbine Rotor

Experience of weld repair of geothermal turbine rotor is introduced below.

Experience is to repair turbine rotor for 63MW geothermal power plant in Philippine, which detailed specifications are shown in Table 6. Because it was confirmed at periodic inspection that there were large cracks in the first stage of rotor, the damaged part was entirely removed and re-formed by welding and machined as shown in Figure 8.

This turbine is under commercial operation without any problems until now since weld repair.

4. Conclusion

It is confirmed that 12%Cr steel rotor forging and weld repaired rotor by 12%Cr steel welding material are sufficiently reliable to geothermal turbine by verification tests.

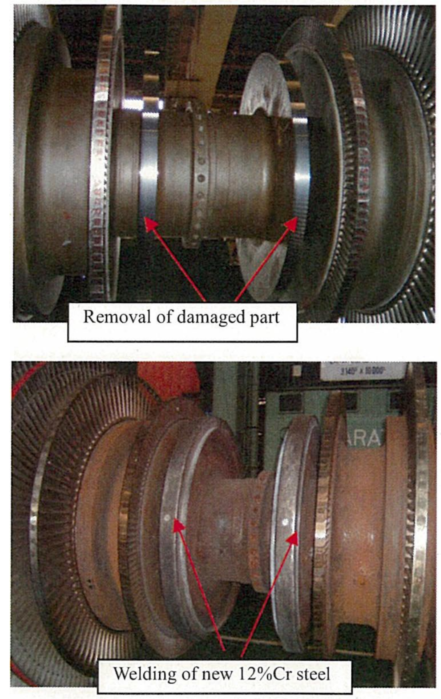

Figure 8. Weld Repair of Damaged Part of Turbine Rotor for Geothermal Power Plant in Philippine.

Table 6. Specification of Geothermal Turbine (Application Experience of Weld Repair by 12%Cr Steel for Rotor).

Country	Philippine
Plant Cycle	Single Flash, Condensing
Output	63.2 MW
Steam Condition - Pressure - Temperature	 8.0 ata 169.6 degree C
Exhaust Pressure	0.135 ata
Turbine	SC2F-25" Single-Cylinder, Double Flow Impulse-Reaction Condensing Turbine
Rotor Weight	22.5 ton

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