Geothermal Resources Council, TRANSACTIONS, Vol. 13, October 1989

WELD REPAIR OF GEOTHERMAL TURBINE ROTORS

Craig E. Chaney

Pacific Gas and Electric Company, Engineering Dept.,
77 Beale St., San Francisco, CA

ABSTRACT

In the past ten years PG&E has been experiencing stress corrosion cracking in its geothermal turbine rotors at an increasing rate. The Geysers Turbine Rotor Restoration Project was formed to develop cost-effective alternatives to replacing damaged rotors. One of the primary alternatives evaluated by the project has been the weld repair of turbine rotors. This paper describes some of the unique metallurgical requirements that were considered when a 55 MW turbine rotor was weld repaired for the power plant. It also points out how turbine rotor welding technology may be exploited in the future to fabricate dissimilar metal rotors that will have superior resistance to stress corrosion cracking and general erosion/corrosion damage.

INTRODUCTION

In 1979, PG&E discovered for the first time stress corrosion cracking (SCC) in a turbine rotor at The Geysers. Since that time, stress corrosion cracking has been identified in an increasing number of rotors and units at the plants. On a number of rotors the cracking has caused extensive damage, and in two cases removal of both second stage wheels was necessary to keep the rotors serviceable.

PG&E formed the Geysers Turbine Rotor Restoration Project to identify and implement cost-effective alternatives to purchasing new replacement turbine rotors due to SCC damage. The project, now well underway, has taken a multifaceted approach in achieving its goal. One of the primary alternatives the project has evaluated is the feasibility and demonstration of weld repairing a geothermal turbine.

First, This paper will give an overview of the history of stress corrosion cracking in the turbine rotors at PG&E's Geysers Power Plants. Using this background as a foundation, the paper will then discuss the unique metallurgical considerations used in evaluating and making a weld repair on a 55 MW geothermal turbine rotor.

STEAM TURBINES AT THE GEYSERS

Currently there are 19 operating units at The Geysers Power Plants producing approximately 1,361 MW of power. 13 of these 19 units are turbine-generator sets manufactured by Toshiba. Since the large majority of the turbines are Toshiba, the Geysers Turbine Rotor Restoration Project is initially focusing its efforts on these turbines.

Of the 13 Toshiba turbine-generator sets, six are 55 MW design and the remaining seven are 110 MW design. Including the spares, there are 28 Toshiba turbine rotors at The Geysers. The 55 MW Toshiba turbines consist of a single, six stage, double flow rotor. The 110 MW machines have two six stage double flow rotors connected in tandem to the generator. These 110 MW rotors are referred to as A and B rotors, where the A rotor is the front rotor in the turbine-generator set and the B rotor is coupled directly to the generator. All three types of rotors (55 MW, 110 MW-A, and 110 MW-B) have similar steam path designs. Hence development efforts on any one of these rotor types will, in most cases, be applicable to the remaining two.

HISTORY OF SCC IN GEYSERS TURBINE ROTORS

Figure 1 shows where SCC occurs on the rotor. These areas are the shaft-to-wheel radii on the second and third stages, the steam balance holes in the second stages, the notch block holes on stages 1 thru 5, and the hook radii in the blade attachment area of stages 1 thru 5. All of these areas are the high stress regions of the rotor that have stress levels between 145 to 310 MPa (21 - 45 ksi).

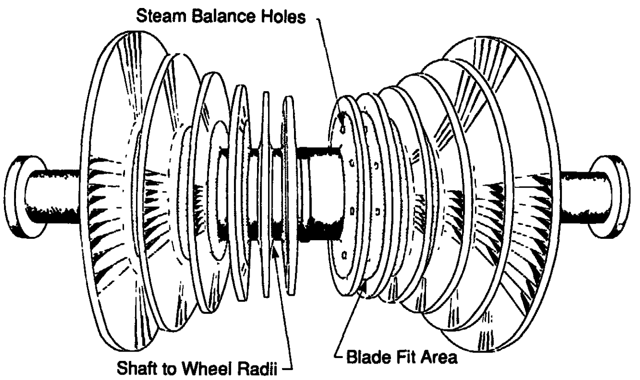

Figure 1. Wide Angle View of Turbine Rotor Showing Locations Where SCC is Predominant

Since 1979, PG&E has been discovering SCC in their turbine rotors at an increasing rate. Figure 2 shows the number of incidents of rotor SCC found per year in the two primary SCC areas of PG&E rotors: shaft-to-wheel radii and the blade attachment area.

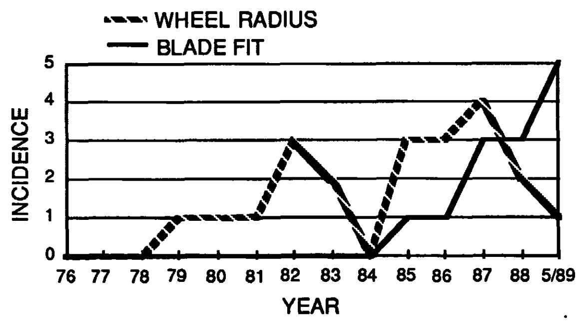

Figure 2. Incidence of Turbine Rotor SCC Per Year at The Geysers

Figure 2 also shows that the incidence of cracking in the shaft-to-wheel radii has recently started to decline. This decrease is attributed to the routine shot peening that has been performed in these areas over the past six years. The shot peening induces residual compressive stresses into the rotor surface and thereby increases the time for SCC to initiate. However, this compressive surface layer can be corroded or eroded away during service, which makes it necessary to re-peen at intervals depending on the steam conditions in the turbine.

In contrast to the shaft-to-wheel radii, the blade fit areas of the rotors have experienced increasing incidences of cracking. The large increase in 1989 can be partially attributed to the inspection efforts to detect cracking in this area. However, prior to the increased inspection efforts (before 1988), the total number of occurrences per year had gradually increased over time, which indicates that the increased incidence of cracking is attributable to factors other than inspection frequency. Since the blade fit area is one of the most highly stressed regions of the rotor and cannot be routinely shot peened, it is expected that it will continue to be one of the more crack sensitive areas on the rotor shaft.

ROTOR RESTORATION PROJECT

In prior years, cracks found in rotors were removed by grinding or machining. After grinding, the turbine manufacturer would evaluate the excavated cavity to determine its effect on the structural integrity of the rotor. If the structural integrity was questionable, the manufacturer would recommend the removal or modification of the affected wheels and the possible replacement of the rotor.

The increasing incidence of SCC made it obvious that The Geysers Power Plants would continue to face situations requiring wheel modifications or removal and replacement of turbine rotors. Since curtailment costs of operating a turbine with missing stages are in the millions of dollars over the remaining life of the unit and the costs of new replacement rotors are also in the millions, PG&E needed to develop methods to mitigate the SCC and repair damaged turbine rotors.

To develop and evaluate alternatives to operating rotors with missing stages and/or the purchase of new rotors, the Geysers Turbine Rotor Restoration Project was formed. The project took a multifaceted approach in developing cost-effective alternatives. Some of the alternatives the project is exploring are briefly described below:

- Evaluate and demonstrate the feasibility of restoring by weld repair existing damaged spare rotors.
- Develop NDE techniques to inspect the blade fit areas of the rotor for SCC without removing the blades.
- Perform a fracture mechanics analysis of the blade fit area to determine the critical size crack to cause failure.
- Improve the understanding of what constituents and characteristics of the steam are the most influential in causing stress corrosion crack growth. Investigate means to alter the steam chemistry to mitigate cracking.

One of the primary tasks of the project is to evaluate and demonstrate a weld repair on a geothermal turbine rotor.

TECHNICAL CONSIDERATIONS

In the last ten years some domestic turbine manufacturers have started to weld repair turbine rotors from fossil and nuclear power stations. It was the intent of the project to adapt this existing technology to meet the special metallurgical requirements of a turbine rotor operating in the geothermal steam at The Geysers. The project evaluated this technology and contracted with ASEA Brown Boveri to weld repair one 55 MW turbine rotor. The repair is near completion at the time of this writing and the rotor is scheduled to be returned to service in September 1989.

Rotor Weld Repair Types

Figure 3 shows the three primary types of weld repairs that will be used to repair the SCC damage at The Geysers.

A Type I repair is the repair of the blade fit region where either SCC has occurred to a depth that violates design standards or the fit is sufficiently deteriorated so that the clearances between the blades and the fit are excessive and may jeopardize blade life.

A Type II repair is used to rebuild a wheel that has been previously machined off at the rotor shaft surface. The wheels were removed due to extensive cracking at the shaft-to-wheel radii. The entire wheel, approximately 89 cm (35 in.) in diameter, is rebuilt with weld filler material.

A Type III repair is for the repair of SCC at the shaft-to-wheel radii. This type of repair was performed on a rotor in 1983. However, the rotor was only recently returned to service due to the metallurgical concerns.

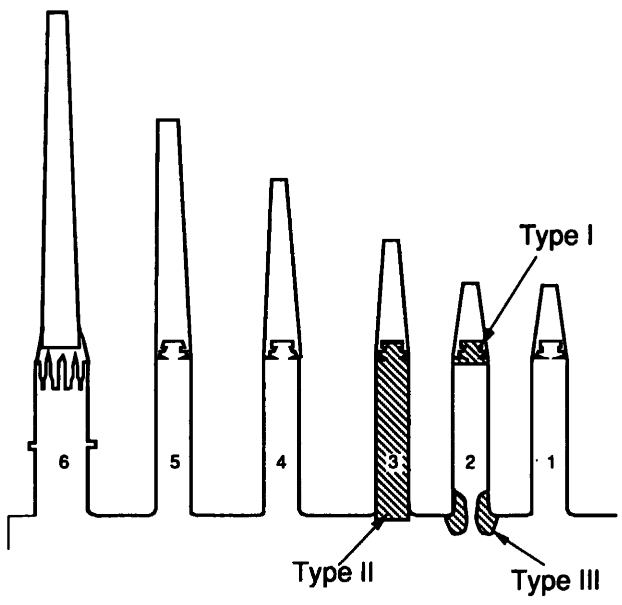

Figure 3. Primary Types of Weld Repairs on The Geysers Turbines

Metallurgical Considerations

Weld repairing turbine rotors that operate in a geothermal environment requires unique metallurgical considerations in comparison to other types of turbine rotors. This is primarily due to the corrosiveness of the geothermal steam. High temperature (425°-590° C) metallurgical considerations for fossil turbine repair, such as creep strength and high temperature embrittlement, are not a concern for the low temperature geothermal rotors. This section of the paper will describe some of the metallurgical considerations and the process used when making a weld repair to a geothermal turbine rotor.

General Procedure For Weld Repair

To assist in understanding some of the metallurgical considerations, a simplified description of the process used in making a weld repair is listed below:

1. Remove the cracked or otherwise damaged material from the rotor by machining.
2. Nondestructively examine the rotor in the area to be welded for any pre-existing flaws. Magnetic particle and ultrasonic examination techniques are usually used.
3. Preheat the rotor to a predetermined temperature for the duration of the welding.
4. Deposit the weld material with an automatic welding process such as submerged arc welding or gas tungsten arc welding. This requires the welding to go on around the clock often for weeks at a time.
5. Post weld heat treat the rotor to temper (soften) the base and weld metal and reduce residual stresses.
6. Rough machine the wheel.
7. Perform magnetic particle and ultrasonic examinations.
8. Final machine wheels and blade fits.
9. Magnetic particle inspect the final machined surface.

In general, the criterion of developing a weld repair procedure for a geothermal turbine rotor is selecting the appropriate weld filler material that will meet the minimum design tensile strength requirements of the rotor, after it has been post weld heat treated. The post weld heat treatment should be performed at a sufficiently high temperature to lower the heat affected zone (HAZ) hardness of the base metal to an acceptable level. It is important to minimize the HAZ hardness since the susceptibility to SCC increases with hardness.

In addition the weldment should be of a material that is more resistant to SCC than the rotor material to increase the longevity of the repair.

Base Material
The first consideration when designing a weld repair is the chemical composition of the base material. Its strength and resistance to tempering during post weld heat treatment is of the utmost importance in the development of the weld procedure. The two types of rotor materials used at The Geysers are an ASTM A470, Class 8 CrMoV material and an ASTM A470, Class 6 3.5% NiCrMoV material. The A470 Class 8 material has been weld repaired twice at The Geysers. The Class 6 material has not yet been weld repaired at The Geysers and may pose some difficulty in reducing the HAZ hardness to acceptable levels.

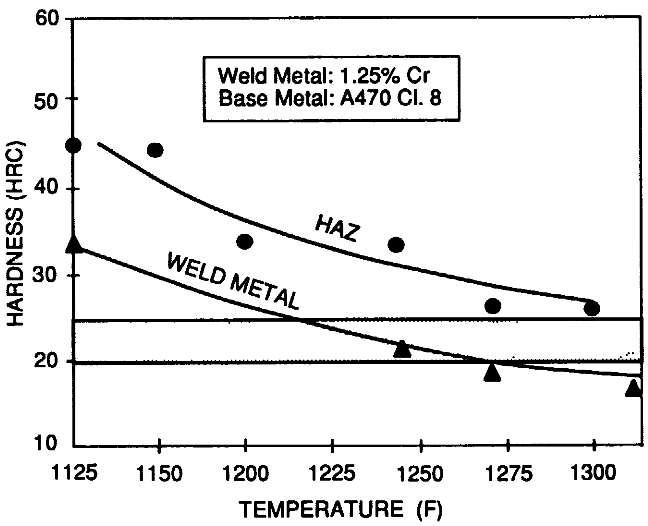

Figure 4. Tempering Curve for a Welded CrMoV Rotor Material (HRC reading converted from actual HK readings.)

Heat Affected Zone
Figure 4 is a tempering curve of a heat affected zone of an ASTM A470, Class 8 (CrMoV) turbine rotor forging that was welded with a 1.25% Cr filler material. This curve demonstrates the balancing act between maintaining weld metal strength and minimizing HAZ hardness. The minimum specified tensile strength of 690 MPa (HRC 20) for the rotor could not be achieved if the rotor was post weld heat treated at 720° C. A 720° C temperature for post weld heat treatment would be desirable because it would temper (soften) the heat affected zone to HRC 25, which would be less susceptible to SCC than a HAZ with a higher hardness. However, at this temperature Figure 4 shows the weld metal would fall below the minimum tensile requirements of 690 MPa (HRC 20), which would be unacceptable. A compromise in post weld heat treatment temperature of 690° C was made to keep the weld metal strength above the minimum of 100 ksi and the final hardness of HRC 28.

Since the HAZ is expected to be the most susceptible zone of the weldment to SCC, it is important to design the weld joint so that it is in a low stress region. For example, the HAZ in a Type I repair is immediately below the blade fit transition. Raising the HAZ into the blade fit region would be unacceptable due to the much higher stress field present in that region. The stress field below the blade fit region gradually increases towards the shaft because of the increasing rotating mass.

SCC of Weld Metal
Another consideration for geothermal applications is the SCC resistance of the weld filler material. Selecting the filler chemistry to approximate the rotor material chemistry is likely to produce a weldment with a similar susceptibility to SCC as the rotor material. This would result in a significant possibility that the repair would re-crack in service.

However, making a weld repair on a turbine rotor provides an excellent opportunity to place materials with superior SCC resistance in the area of the rotor that is most susceptible to SCC. In the recent weld repair of The Geysers' 009 rotor, a 12% chromium weld material was selected to rebuild the second stage wheels (Type II repair).

This weld material was selected because it is expected to provide a two-fold benefit. First, the 12% Cr weld material is expected to have superior SCC resistance to the rotor material. The 12% Cr filler material is similar in composition and strength to the turbine blade material which has not been found subject to SCC in The Geysers steam environment. Second, the weld material can be post weld heat treated at a higher temperature and still maintain ultimate tensile strengths greater than 15.9 MPa (110 ksi). The usage of a higher post weld heat treat temperature will lower the heat affected zone hardness to levels that may be more resistant to SCC and general corrosion.

SPECIFICATION FOR WELD REPAIRS

A technical specification for weld repairing any turbine rotor would be beneficial to both the contractor and the owner. However, due to the unique steam environment in which a geothermal rotor operates, a technical specification is essential for a successful repair. A contractor who may be completely familiar with turbine rotor weld repairs for fossil and nuclear power plants may not be aware of the unique metallurgical considerations in making a weld repair to a geothermal rotor.

Some of the requirements that should be listed in a technical specification are given below:

1. The ASTM specification and class of the rotor material.

2. The specified minimum tensile strength (ultimate and yield) of the composite weld joint. This should be same as the specified minimums for the rotor material.

3. The location of the HAZ or the right to approve the recommended location.

4. The maximum and minimum hardness of the heat affected zones.

5. Description of qualification test blocks that will be required prior to the welding on the rotor.

6. The type and frequency of nondestructive and destructive testing of the weldment and the rotor.

7. A list of items to be reviewed and/or approved by the client, e.g., weld procedures, HAZ locations, or tolerances.

Weld Qualification Test Blocks

In PG&E's request for proposal to weld repair the 009 rotor, a weld qualification test block of rotor material was specified to be welded and tested prior to the start of welding on the actual rotor. The purpose of the test blocks was to prove that the welding procedure produced a weld that met the technical requirements of the specification. Figure 5 shows the dimensions of the test block for a Type II repair and the orientation of the test specimens removed from the test block. Table I shows some of the test results from the test block.

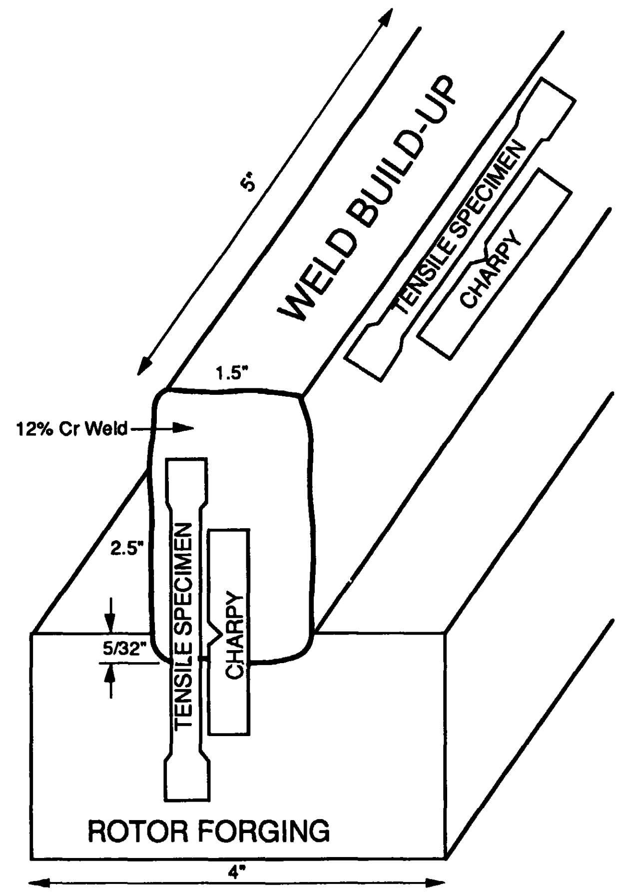

Figure 5. Rotor Weld Qualification Blocks

Weld Qualification Test Block

Zone	Rockwell C (B) Hardness	Tensile Strength MPa (KSI)	Yield Strength MPa (KSI)
Base Metal	(98.3) -22.8	(103 - 104) 710 -718	(78.8 - 80.9) 544 - 558
HAZ	(98.3) - 27.5		
12% Cr Weld	22.2 - 27.1	112 - 115 (773 - 794)	(83.5 - 84.7) 576 - 584

Table I. Weld Qualification Test Block Results

The test block configuration shown in Figure 5 would be suitable for Type I and II repairs. However, the orientation of some of the test specimens should be altered somewhat for the Type I repair to reflect the change in the orientation of crack growth in service.

FEASIBILITY OF WELD REPAIR

Economics

Weld repairs of geothermal turbines may be technically feasible but may not always be economically viable. The cost of weld repairing a large nuclear and fossil turbines is relatively small to their replacement value of up to $10 million. However, the benefit/cost ratios of weld repairing the smaller geothermal rotors that may have extensive blade damage can be much lower. At the time of this writing, the cost of making a Type I weld repair is approximately $200,000 to $400,000 for two stages (not including replacement blades). If the remainder of the rotor is in good condition a weld repair may be economically viable. However, if for example, four or more stages are in need of repair or the condition of the blades is marginal, the repair may not be economical over the purchase of a new rotor. The circumstances for the given situation such as lead times for repairs and obtaining replacement rotors, spare rotor status, and current cost for repairs should also be evaluated.

Risks

In recent years foreign and several domestic turbine manufacturers have developed turbine welding capabilities and are routinely weld repairing turbine rotors for fossil and nuclear applications. Clearly weld repair is a viable option in these types of power plants. However there is very limited experience with welded turbine rotors in geothermal environments. At the time of this writing, PG&E has had only two months of operation on its first weld repaired rotor. Though it is expected that the weld repaired rotors will perform satisfactorily at The Geysers, it should be recognized that these options are based on engineering judgement. There is a risk of unforeseen problems that may develop in service that would make weld repairs unsuitable at The Geysers. This risk is believed to be primarily associated with the corrosive interactions of the steam with the weld metal and HAZ. Residual stresses induced from welding may also be a source of some unforeseen problems.

WELDED CONSTRUCTION FOR NEW ROTORS

The incidence of SCC of PG&E's Geysers turbine rotors has been increasing and is expected to continue, especially in the blade fit area of the rotors. Areas such as the wheel-to-shaft radii may be routinely shot peened, coated, or redesigned to mitigate SCC. The blade fit regions, on the other hand, are inaccessible for routine maintenance procedures such as shot peening and are inherently one of the highest stressed regions of the rotors. These areas are therefore the most likely to crack.

The ability to selectively apply specialized high strength corrosion resistant alloys to highly stressed regions of new rotors via welding may be a cost-effective solution to SCC. Use of a high alloy material as the sole material for the rotor, as would be with conventional rotor fabrication, would be uneconomical. New generation rotors could be welded fabrications from dissimilar materials utilizing high alloy materials in limited locations. This type of technology is not new. Stainless steel clad plate, hard facing, and even metallic coatings are just a few examples of cost-effectively placing the specialized, more costly alloy only where it is needed. It is recommended when evaluating repairs to existing rotors or purchasing new rotors, the application of this technology be explored with the various turbine manufacturers that have turbine welding capabilities.

CONCLUSIONS

The incidence of SCC in PG&E geothermal turbine rotors has dramatically increased over the past 10 years. The SCC has damaged more than 14 rotors at The Geysers; four of these rotors have had or will require modification to some of their stages. PG&E expects that the SCC will continue to be a prominent problem in operating and maintaining geothermal units in the future.

To continue operating these geothermal units, cost-effective methods will need to be developed to repair and mitigate SCC damage to the rotors. One of the methods recently explored at PG&E is weld repairing the turbine rotors. By meeting unique metallurgical requirements the weld repair of an A470 Class 8 rotor was shown to be technically feasible. However, the current cost of this type of repair may not be economically viable for all situations. Rotors requiring an extensive amount of repair may have repair cost that are a high percentage of a new rotor. A case-by-case economic analysis including other factors such as lead time and the availability of spare rotors should be performed.

The ability to apply high strength corrosion resistant alloys to specific high stress locations on the rotor via welding can significantly increase the resistance of rotors to SCC. We believe that by adapting the current rotor welding technology to the fabrication of dissimilar metal geothermal rotors, the challenges of geothermal corrosion could be economically met in the future.

ACKNOWLEDGEMENT

The author wishes to express his gratitude for the support and guidance of both PG&E's West and East Geysers Power Plants and PG&E's Research and Development Department. A special thank you goes out to all the people who have reviewed drafts of this paper and provided invaluable feedback on its content.