Geothermal Resources Council TRANSACTIONS, Vol. 16, October 1992

WELD REPAIR OF GEOTHERMAL TURBINE ROTORS
A PARTNERING APPROACH
BY
PACIFIC GAS AND ELECTRIC CO. AND ASEA BROWN BOVERI

Donna L. Schubert(1) Michael D. Morin(2) Timothy W. Hollingshead(3)

(1) Metallurgical and Welding Consulting Services, 1150 Maraschino Drive, Sunnyvale, CA 94087
(2) ASEA Brown Boveri Steam Power Generation, Inc., 1200 Willis Road, Richmond, VA 23237
(3) Pacific Gas and Electric Co., Geysers Power Plant, P. O. Box 456, Healdsburg, CA 95448

ABSTRACT

Over the past thirteen years PG&E has experienced stress corrosion cracking (SCC) in its geothermal turbine rotors. This paper describes the unique approach taken to resolve the metallurgical requirements considered when turbine rotors were weld repaired for the power plant. A partnership approach, with a full and free exchange of information, was utilized by Pacific Gas and Electric (PG&E) and ASEA Brown Boveri (ABB) to overcome the technical problems and successfully weld repair four Geysers rotors to date. The most challenging of these was the 14A rotor with the entire replacement of both flows of the second and third stages.

INTRODUCTION

In 1961 the first PG&E geothermal steam generation unit went into commercial operation at PG&E's Geysers Power Plant with an installed capacity of 12.5mw. Because of the successful operation of Geysers Unit 1, PG&E undertook an expansion project which spanned the next three decades and resulted in a maximum installed generation capacity of 1361mw's.

SCC in a Geysers turbine rotor was first discovered by PG&E in 1979 and has been an ever increasing problem since that time.

PG&E's Unit 14 went into service on September 12, 1980. Unit 14 is a 114mw rated turbine generator set utilizing a 4 flow, tandem rotor (A and B rotors) steam turbine as prime mover. The unit operated for a 20 month period prior to its first inspection. During this inspection, SCC was found on both turbine rotors in the shaft to wheel transition radii of the 2nd stages. The turbine manufacturer recommended grinding the SCC to remove all cracks from the rotor. After this work was completed, it was determined the SCC on the A rotor was so severe the structural integrity of the rotor was in question. It was determined the rotor should not be put back in service.

In 1983 PG&E entered into a contract with Brown Boveri Turbomachinery, Inc. (BBC) of St. Cloud, Minnesota to perform weld repairs on the second stages of the 14A turbine rotor. The contracted repairs consisted of machining into the second stage wheel transition area to remove all traces of SCC and then welding out the transition radii with material similar to the original rotor material. After completion of the welding, the transition was machined to a new, heavier configuration, leaving more material and a larger radius in the area. The contracted repairs were completed by BBC in their St. Cloud facility and the rotor was returned to the Geysers. Because of several technical questions and concerns raised by the turbine manufacturer, the 14A rotor was not put back into service until April of 1989. Nineteen months later, in November 1990, the 14A rotor was removed for inspection. This inspection found numerous problems with the 14A rotor, primarily, cracked second stage blades and wheel transition radii cracks on the third stages of both flows. There were no problems noted on the BBC weld repaired areas of the second stages. After the second stage blading was removed, the blade fit area was inspected. Numerous stress corrosion cracks were found in the blade fit area.

During 1989 and 1990 PG&E had contracted with ABB for the weld repair of two turbine rotors in their Richmond, Virginia facility. The second stage wheels were replaced entirely on one rotor and the second stage blade fit area was replaced on the other. Because of the success of these repairs, PG&E decided to replace all four wheels of the second and third stages of the 14A rotor. The decision to replace the second stages was based on the advantage of replacing the original rotor material with material less susceptible to SCC.

ABB was chosen for the 14A rotor weld repair for several reasons: As a steam turbine manufacturer, ABB has used a weld fabrication technique for producing their own rotors for over 60 years. No other organization in the world has their experience with rotor welding. More important to PG&E was the fact ABB was willing to work with PG&E to determine new processes and materials for the rotor weld repairs to help resolve the inherent problems with steam turbine rotors in a geothermal environment. ABB accepted PG&E as "partners" with valuable skills and knowledge in this ongoing project. This partnership approach has resulted in the successful weld repair of four Geysers rotors, including the 14A rotor, which has been the most technically challenging geothermal rotor ever weld repaired.

THE STRATEGY

The susceptibility to SCC can be significantly reduced by replacing material which is known to be sensitive to SCC with material which has proven by operation in the same environment to possess increased resistance to SCC.

This is our approach to the repair of the Geysers units. The 1-1/4CrMoV base material had fallen victim to SCC quite regularly. However, the 12%Cr blades operating in the same bulk steam environment at the end of the wheels had a greater resistance. To simply replace the damaged 1-1/4CrMoV with a similar material would give new life to the rotor, but the SCC problem would certainly return. Replacing the wheels with a material similar to the blade material would renew the rotor and minimize future occurrences of SCC.

With this in mind, several repair scenarios were developed using 12%Cr filler metal. They ranged from replacing material in the transition radius on interstage packing seal areas either side of the wheel, to the replacement of the blade fit areas, to the replacement of the entire wheel.

Each rotor was to be judged on a case by case basis to determine the appropriate repair. In addition to the inherently greater corrosion resistance of the 12%Cr weld metal, improved resistance to SCC was obtained by controlling the hardness of the 12%Cr weld metal deposit through a subcritical anneal heat treatment. This required heat treating tests on a case by case basis as well, in order not to sacrifice base metal strength while performing the optimum postweld heat treatment (PWHT) for SCC resistance.

In the case of the 14A rotor, PG&E decided to replace the entire wheel in the second and third stages, both flows. This included the transition radii and the interstage packing area.

LABORATORY EVALUATION OF A TEST WELDMENT

The successful weld repair of a geothermal steam turbine rotor requires consideration of the rotor base metal composition and mechanical properties, selection of an appropriate weld filler material, control of the parameters used during production of the weld deposit, and the proper application of PWHT. Because each rotor weld repair presents a unique case of rotor base metal properties, a test weldment is produced using the actual rotor material base metal. Evaluation of this test block's response to PWHT is performed to insure that the completed weld repaired rotor's properties will render it suitable for service in a geothermal steam environment.

The properties required for a successful weld repaired rotor for geothermal service are somewhat different compared to those required for conventional steam turbine environments. High temperature phenomena such as creep and elevated temperature embrittlement do not occur in geothermal steam turbines. On the other hand, geothermal steam impurities such as chlorides, hydrogen sulfide, and high levels of silica present unique corrosion considerations. In particular, SCC resistance must be maintained or even improved in the weld repaired rotor.

The test weldment was designed, produced, and evaluated with the following considerations in mind: Simulation of an actual rotor weld repair in terms of the critical parameters such as base metal composition, base metal response to thermal operations such as welding, preheat and postweld heat treatment, and weld deposit material response to postweld heat treatment.

Based on the results of previous laboratory evaluations of test weldments, the Rotor 14A test weldment was subjected to three different postweld heat treatment temperatures in order to determine the optimum temperature which would maintain minimum required tensile properties in the rotor base metal while at the same time tempering the 12%Cr weld deposit and the rotor base metal heat affected zone (HAZ) for improved resistance to SCC.

The test weldment base metal was removed from the Rotor 14A second stage wheel as shown in Figure 1. Hardness measurements were made on the Rotor 14A material prior to welding. Previous testing had established the material's tensile properties prior to welding in the thru-thickness direction in a area of the wheel comparable to that from which the test coupon was removed.

These properties were used for comparison with the test weldment's properties after several different postweld heat treatments to determine the effect of welding and PWHT on rotor mechanical properties.

Hardness	Yield Strength	Ultimate Tensile Strength	Elongation
HRC 21-25	80-83 ksi	106-108 ksi	20%-21%

The chemical composition of the Rotor 14A material is shown in Table 1, along with selected requirements for ASTM A470 Class 8 material.

Element	C	Cr	Mn	Mo	Ni	Si	V
Rotor 14A	0.30	1.06	0 .80	1.26	0.51	0.30	0.25
ASTM A470 Cl 8	0.25 0.35	1.05 1.50	1.00 max	1.00 1.50	0.75 max	0.15 0.35	0.20 0.30

Table 1

Welding of the test weldment was performed in accordance with the procedures followed for rotor weld repair. Preheat, interpass temperature, and preheat maintenance as well as heat input were controlled to produce a test weldment which simulated an actual rotor weld.

The test weldment was then subjected to three separate subcritical anneal heat treatments: 1280°F for 12 hours soak, 1260°F for 12 hours soak, and 1250°F for 12 hours soak. These temperatures were chosen based on the results of pervious heat treatment investigations and the resultant tensile and hardness properties of similar test weldments. Heat treatment was performed in a laboratory furnace and thermocouples were attached to the coupons to monitor the test coupons' temperatures.

Following heat treatment, the coupons were prepared for hardness evaluation and specimens were removed for tensile testing as shown in Figure 2. Forty Equotip hardness traverses were made across the weld deposit and unaffected base metal and 40 Knoop microhardness traverses were made across the base metal HAZ. The hardness results (calculated as 95% confidence intervals and converted to the Rockwell C or Rockwell B scale) and tensile test results (for transverse composite tensile specimens) for each PWHT temperature are shown in Table 2.

Coupon/Area	1250°F/ 12 hrs.	1260°F/ 12 hrs.	1280°F/ 12 hrs.
Unaffected Base Metal	HRC 21-22	HRC 22-23	HRB 94-96
Base Metal HAZ	HRC 28-29	HRC 26-28	HRB 92-94
12Cr Weld Deposit	HRC 24-25	HRC 25-26	HRC 19-20
Yield Strength	85-92 ksi	76-81 ksi	69-72 ksi
Tensile Strength	109-114 ksi	104-107 ksi	95-98 ksi
Elongation	16%-17%	17%-18%	17%-18%

Table 2

Because the tensile specimen was comprised of the 12%Cr weld deposit, base metal HAZ, and heat treated base metal, only the tensile strength is a valid property measurement to compare with the unwelded rotor base metal. Failure of the tensile specimens occurred in the base metal.

Because of concern that excessive softening (and consequent loss of strength) in the base metal could occur at PWHT temperatures greater than 1280°F, a PWHT cycle of 1270°F for 12 hours was selected for Rotor 14A.

THE REPAIR

The 14A rotor had received the usual blast cleaning and NDE at the PG&E site. In addition, the weld preparation designed by ABB engineers was machined by PG&E before shipping. The weld preparation involved complete removal of the four wheels and approximately one additional radial inch of material from the rotor body diameter (see Figure 3). The rotor arrived at the ABB Richmond, Virginia facility on August 21, 1991. Here, the program started with magnetic particle and ultrasonic inspection of the two weld preparations, as well as hardness profiles of the rotor and weld preparations.

Next, the rotor was set up in the submerged arc welding (SAW) station (see Figure 4). Since the 12%Cr weld build-up material is air hardening, the complete weldment must not be allowed to cool excessively prior to the application of the PWHT. This makes it necessary to attach as much of the resistance heating equipment as possible prior to the start of preheating. In other words: Once the preheat/welding has commenced, the rotor is not allowed to cool until after the completion of the PWHT cycle. In preparation, the rotor is coated with a protective solution to guard against scaling during the high temperatures of the PWHT cycle.

Next, the thermocouples are tack welded in their pre-assigned positions and the ceramic heating pads are secured in place. Finally, insulation covers the arrangement. The heater pad leads are tied off for the rotation during welding. The rotor is then preheated with gas torches while rotating in the horizontal position. Once the appropriate soak time is achieved, several layers of 5%Cr are applied as a butter layer (see Figure 5). This is the same technique used when building up an impulse wheel on an HP rotor. When the entire weld has been buttered, the 12%Cr welding begins. The welding takes place at two SAW stations simultaneously (one at each flow of the LP), and continues around the clock. The form of the four wheels is controlled by measurements and templates (see Figure 6).

The interpass temperature is closely controlled during the welding process in order to promote self-tempering of the martensitic weld deposit, to increase the rate of dissolved hydrogen diffusion, and to minimize the cracking tendency of the weld deposit and heat affected zone. This self-tempering is necessary since the weldment must be cooled to a range around 200°F after welding and before PWHT. At this point, the weld metal would be very susceptible to cracking if only untempered martensite were present.

At the completion of the SAW process, more than 3-1/2 tons of weld wire and 5-1/2 tons of flux had been consumed and the most difficult segment of the operation was about to begin. While the rotor and weld material are still at the interpass temperature, the remainder of the thermocouples, heater pads, and insulation must be attached. Specially designed heaters were manufactured for the narrow spaces between the wheels.

As is the case with PWHT of all rotating equipment, the rotor is turned into a vertical position during heating and cooling to maintain symmetry (see Figure 7). Heater pad cables and thermocouple (TC) wiring are then connected to the power sources and recorders. All this must happen in the time it takes the rotor to cool from the welding interpass temperature to the 220°F preheat maintenance temperature. During this time, any retained austenite is transformed to martensite so that the final weld deposit microstructure prior to the subcritical anneal is approximately 95% tempered and untempered martensite.

Now the weldment is ready for PWHT and tempering of martensite. A conservative rate of heating and cooling are employed. Small variations in the PWHT soak temperature have a significant influence on the base metal final hardness and strength (and to a lesser extent, the weld deposit). Since hardness and strength, in turn, influence the material susceptibility to SCC, it was necessary to hold a very tight tolerance on the soak temperature range. The most critical areas were held within +-10°F.

Following the completion of welding and postweld heat treatment, the rotor was blast cleaned (Figure 8) and the weld build-up areas were rough machined (Figure 9) and inspected with the wet fluorescent Magnetic Particle Testing (MT) and Ultrasonic (UT) methods. MT revealed some shallow indications in the weld deposit which were removed by light grinding. UT did not reveal any reportable indications. The acceptance criteria are the same as would be applied to a new welded rotor.

Numerous hardness readings were taken to profile the welding build-up and rotor base metal areas and are discussed in the next section.

Final machining of the blade fit areas was done in a CNC lathe, and the MT inspection was repeated (see Figure 10). The rotor was shipped at this point on December 5, 1991 (approximately 14 weeks) and the reblading was done on site by PG&E personnel.

EVALUATION OF THE COMPLETED WELD REPAIRED ROTOR

Hardness testing of the completed rotor weld deposit and rotor base metal within 2 inches of the fusion line was done with the portable Equotip method. For the rotor base metal, groups of five readings were made in eight locations spaced evenly around the circumference of the rotor near the first and fourth stages of both the governor and generator ends of the rotor. For the weld deposit, groups of three readings on each side of the second and third stage wheel build-ups and evenly spaced at eight intervals around the wheels' circumferences were made on both the governor and generator ends of the rotor. The Equotip readings in Table 3 are reported as 95% confidence intervals, converted to the Rockwell C hardness scale.

Location/ Hardness				
	Rotor Gov End 1st Stage	Rotor Gov End 4th Stage	Rotor Gen End 1st Stage	Rotor Gen End 4th Stage
Rotor Average: HRC 22-23	HRC 21	HRC 24-25	HRC 23	HRC 21-22
	Weld Dep Gov End 2nd Stage	Weld Dep Gov End 3rd Stage	Weld Dep Gov End 2nd Stage	Weld Dep Gen End 3rd Stage
Weld Average: HRC 27-28	HRC 28	HRC 27	HRC 26-27	HRC 27-28

Table 3

DISCUSSION

The objective to produce a weld repaired rotor with mechanical properties suitable for service and corrosion resistance equal to or better than the original rotor's was accomplished through the careful application of the knowledge gained from the test block weldment laboratory analysis coupled with appropriate control of shop procedures. Because of Rotor 14A's previous thermal treatments, it was not possible to apply the optimum postweld heat treatment (in terms of maximizing resistance to SCC in the weld deposit and base metal HAZ) without risking an unacceptable loss of strength in the rotor base metal. However, the test block results did allow us to apply a higher PWHT temperature to the weld repaired rotor than had been previously thought allowable.

A key problem in development of the procedure for weld repairing CrMoV rotors for Geysers steam service is the presence of a SCC service environment. SCC results from a combination of steam chemistry, design factors and material susceptibility. In turn, operations (better steam chemistry), design modifications to lower stresses, and material improvements (such as 12%Cr weld deposit in the areas of greatest vulnerability) can all be applied to reduce the incidence or rate of cracking. In addition, shot peening is performed to produce a layer of residual compressive stress in the highly stressed areas of the rotors.

SCC occurs when there are tensile stresses (either applied or residual), a preferred path for corrosion attack, and an environment containing harmful species. A notch may initially develop by preferential corrosion at a microstructural inhomogeneity in the material. Cracking can proceed by either anodic dissolution or cathodic hydrogen embrittlement mechanisms. Since both transgranular and intergranular cracks have been observed in rotors at the Geysers, it appears that both mechanisms are operating at different times or in different locations.

The corrosiveness of geothermal steam is a result of the high salt (such as NaCl and KCl) contents, dissolved carbon dioxide levels, presence of hydrogen sulfide, and high levels of calcium carbonate and silica in an acidic solution. Since the solubility of these species in steam decreases as the temperature is reduced by steam expansion, deposits can form on the rotor. The liquid solution contaminant concentration may be increased by wet-dry cyclic conditions, particularly in the region of the Wilson line. Silica deposits can act as sponges to retain and concentrate the corrosive medium.

Since turbine materials have a narrow range of passivity, they are particularly vulnerable to pH and oxygen concentration excursions which can lead to pitting. This passive range is made even more narrow by the presence of chlorides in the turbine environment. SCC often initiates at the base of a pit or at the tip of a notch. Adsorption of sulfide ions catalyzes the anodic dissolution reaction. Concurrently, cathodic reactions (embrittlement by hydrogen product evolution) can occur at cathodic sites on the metal surface or in the walls of the crack. Initially, the electrochemical factor dominates and there is localized breakdown of the protective oxide film followed by the formation of pits or fissures. After SCC initiates, there may be a transition to the mechanical aspect of SCC (stress intensity factor).

CONCLUSION

Since the Geysers steam presents a SCC environment to turbine rotors, successful weld repair must incorporate procedures to promote SCC resistance as well as insure adequate mechanical property requirements. Weld repair of CrMoV rotor material for use in a SCC environment must be performed within the limitations of the rotor material's tendency for hydrogen cracking and the precipitation of carbides in the HAZ and 12%Cr weld deposit's tendency to form brittle martensite during normal cooling. These potential problems have been addressed through the use of adequate preheat, interpass temperature control, and preheat maintenance procedures. In addition, the final weldment's hardness must be controlled by postweld heat treatment to reduce susceptibility to SCC. The rotor base metal and 12%Cr weld deposit differ significantly in their response to heat treatment and so require a temperature/time cycle which will adequately soften the martensite in the weld deposit and temper the hardened HAZ of the rotor base metal without excessively softening and weakening the rotor base metal.

The use of test weldments to successfully simulate the rotor material's response to welding and PWHT and so predict their effects on both the rotor material's strength and the weldment's hardness and SCC resistance is a result of the cooperative efforts of both the client and vendor to develop the testing program, shop procedures, and thermal controls necessary to insure the serviceability of weld repaired rotors for geothermal steam service at the Geysers.

ACKNOWLEDGMENT

The authors gratefully acknowledge the efforts of Mr. Guy Faber, Chief Metallurgist for ABB Power Generation Ltd., Baden, Switzerland. His help through the course of this project significantly contributed to its successful completion.

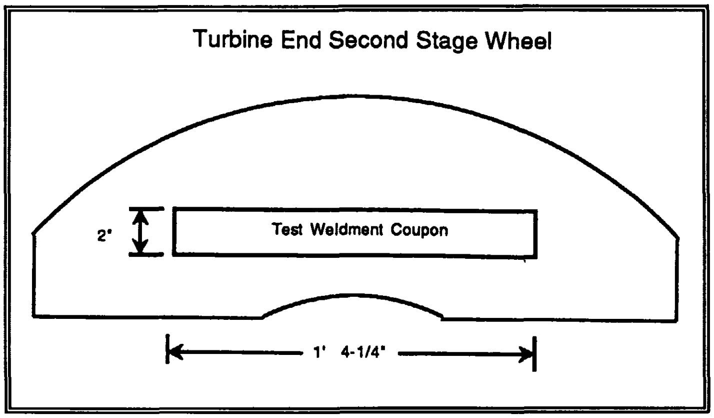

Figure 1 - Test Weldment

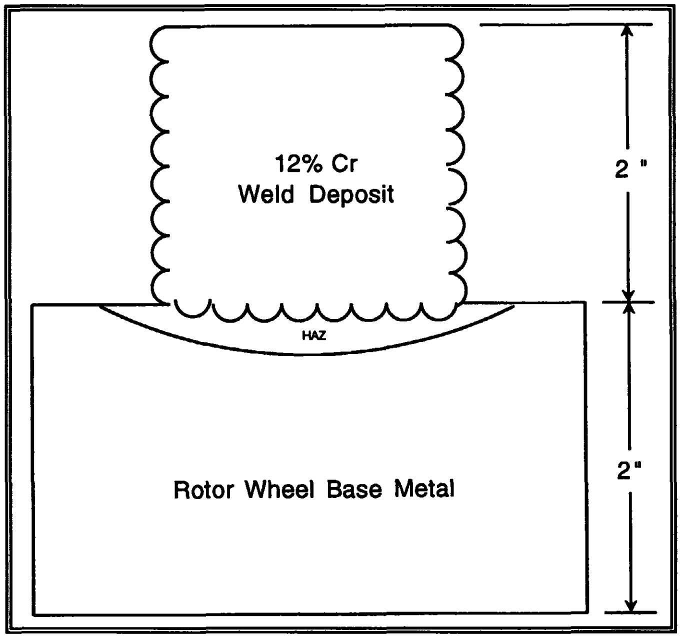

Figure 2 - Tensile Testing Specimen

Figure 3 - Weld Preparation

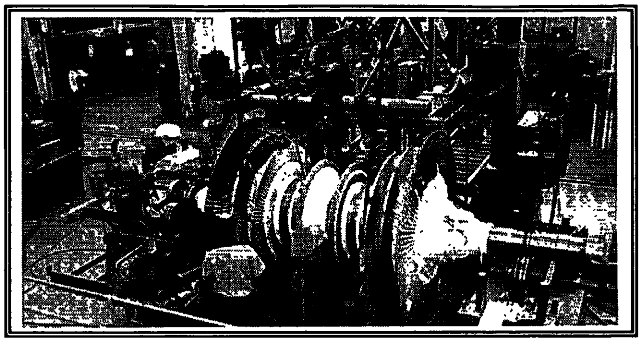

Figure 4 - Saw Set-Up

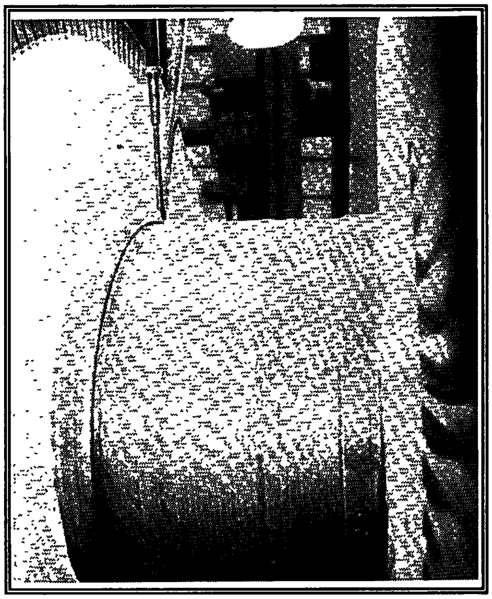

Figure 5 - 5%Cr - Butter Layer

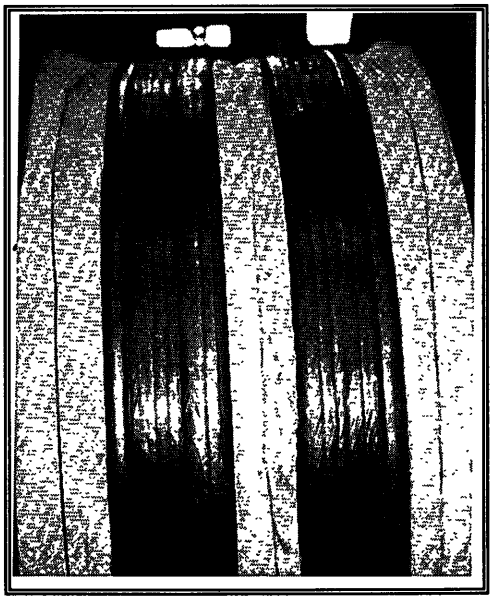

Figure 6 - Wheels Forming from 12%Cr Weld Deposit

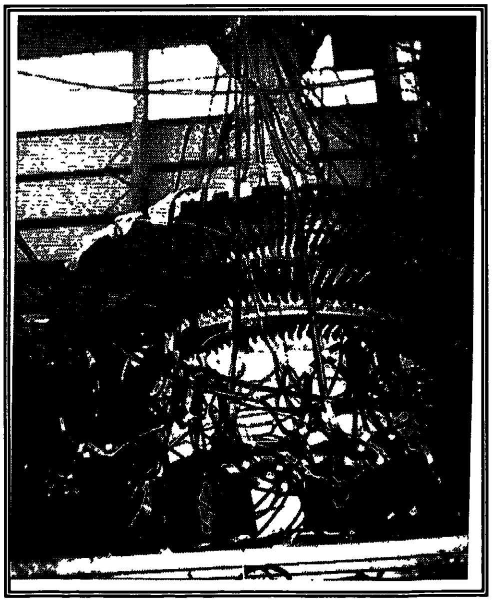

Figure 7 - Post-Weld Heat Treatment

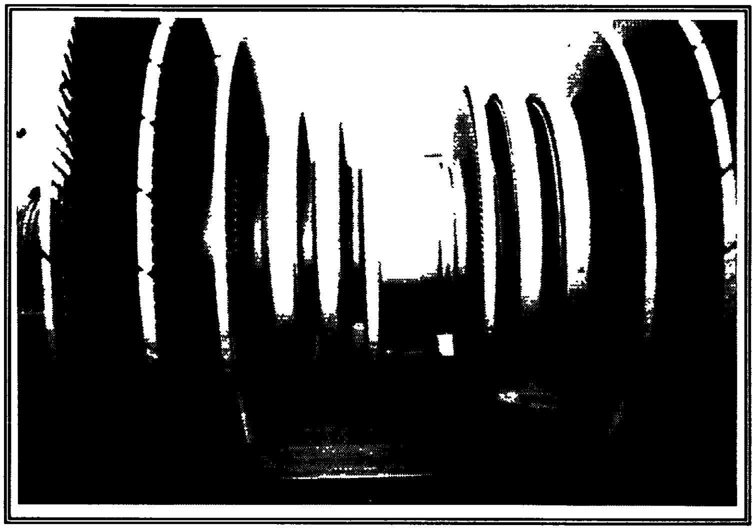

Figure 8 - After Grit Blast

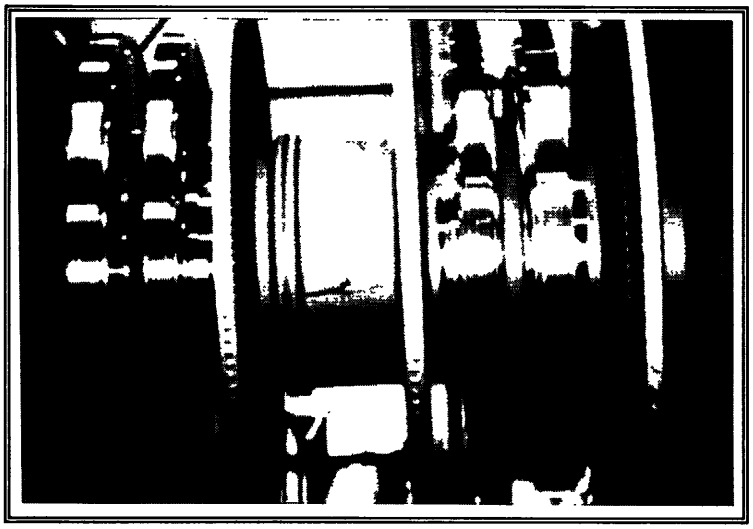

Figure 9 - Blocked Off for UT Inspection

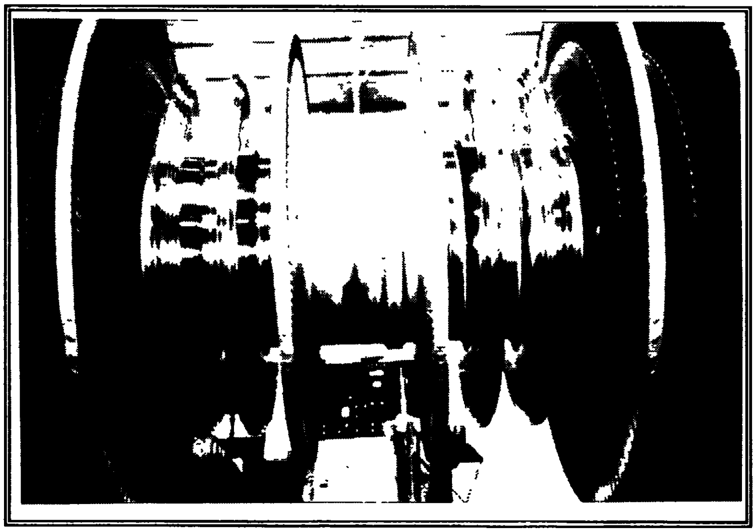

Figure 10 - Final Machining