ADVANCED FABRICATED 10 Cr ROTOR TECHNOLOGY FOR INCREASED EFFICIENCY

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Abstract

It is well understood that higher steam temperatures enable increased operational efficiencies. For supercritical conditions, the forging best suited for elevated temperatures is X12CrMoWVNb10-1-1, or the advanced 10 Cr steel. This was developed by the European COST 501 programme for operations at 600°C. The 10 Cr is excellent for its high strength as well as its enhanced creep life and creep strength properties.

For single cylinder machines it was realized that a composite rotor would be needed. In the areas of lower operating temperatures where the blades are larger and have increased diameters, there is a need for improved mechanical properties over the 10 Cr rotor forging. The optimum forging for these demanding conditions is the 3.5NiCrMoV which has superior high cycle fatigue strength and life, increased toughness, and higher yield strength.

The challenges, however, are to weld and properly heat-treat a fabricated rotor where the two forgings have large dissimilarities in chemical composition and physical properties. A three-year research project investigated and solved the problems associated with all the phases of welding and heat treatment, including 2 scaled prototypes.

Since the completion of the program, the welding procedure has been applied to a number of 10 Cr rotors with service issues in the lower temperature area. The stub ends of the 10 Cr rotors were removed and replaced with 3.5NiCrMoV forgings for more resistance to high cycle fatigue cracking.

This paper will elaborate on the challenges as well as the benefits of composite fabrications, testing and mechanical property data. A case history will also be included for service repairs made to date to older 10 Cr rotors.

Keywords

Neural network analysis
Narrow gap welding
Supercritical steam turbine
Dissimilar steel welding
Welded rotor

Introduction

There are thousands of 10Cr to 13Cr class rotors operating worldwide. Although creep resistance has been good for this class of rotors, several have developed high cycle fatigue cracks in the lower temperature shaft-end areas, some requiring a weld repair. A cost effective solution by Siemens was to cut-off the affected shaft ends and to narrow-groove-weld replacement stub shafts to the original rotor body. Based on the results from this work, it was decided to fabricate composite rotors with 3.5NiCrMoV in the low-temperature highly-stressed parts of the rotor which are susceptible to high cycle fatigue, and creep resistant steel on HP (high pressure) or IP (intermediate pressure) parts of the rotor. The better properties of 3.5NiCrMoV with respect to high-cycle fatigue (HCF) resistance, toughness, and strength make it an excellent choice for HP or IP turbines in areas not subjected to creep. The methods and processes used for the service rotor stub shaft replacement were the same as those developed in the research project for new rotor fabrication.

Since the completion of the project**,** three conventional 10.5 Cr steam turbine rotors have been repaired by cutting off both ends and welding on new 3.5NiCrMoV stub ends using narrow groove gas tungsten arc welding.

Background of Higher Chromium Content Rotors

For high temperature service, the 1CrMoV has been used worldwide for over four decades. The term 1CrMoV is generic, associated with alloy designations such as ASTM A293, class 6, A470 class 8 and A471, classes 1 to 3.

The 12Cr class of rotor forgings was developed in Europe in the 1950s for improved properties at elevated temperatures. Similar forgings were used in the United States circa 1960 and adopted in Japan much later. The term 12Cr is a generic name that applies to alloys with chromium content between 10 and 13 wt%. The advanced 10 wt% Cr class is a subset of the broader 12Cr class with a nominal 10 wt% Cr, with other optimizations on chemical composition and the manufacturing process.

Characteristics of 10 Cr Rotors

There are advantages that 10 Cr forgings have over lower alloyed forgings, particularly the ability to operate at temperatures up to 1130°F (610°C) because of their higher strength, enhanced creep life and creep strength (Figure. 1, where nominal concentrations are plotted). Even with the higher strength, the advanced 10Cr forgings exhibit good ductility and toughness due to the martensitic structure and the balance in chemical composition. Furthermore, the advanced 10Cr rotor forging, as compared to 12Cr alloys such as the X20 and X22, exhibit markedly better weldability and a more favorable response to heat treatment.

While the 10Cr rotor forgings, as well as the entire class of 12Cr rotor forgings, exhibit many desirable properties, there are some disadvantages. The higher chromium content makes the forging more expensive than the lower alloy forgings, and there are fewer suppliers offering the higher alloyed forgings. However, the most problematic characteristic of higher chromium rotors is the phenomenon of “wire wooling”, resulting in very fine metal shavings. This problem occurs when the chromium content exceeds 3 wt%. Rotor manufacturers deal with this in several ways, including using low alloy sleeves or using low alloy filler material to weld the rotor journal areas.

steel	C	Cr	Mo	W	V	Nb	N	(weight%)
1CrMoV	0.28	1.0	0.9	-	0.30	-	-	
12CrMoV	0.21	12.0	1.0	-	0.30	-	-	
10CrMoV	0.12	10.0	1.5	-	0.20	0.05	0.05	
10CrMoWV	0.12	10.0	1.0	1.0	0.20	0.05	0.05	

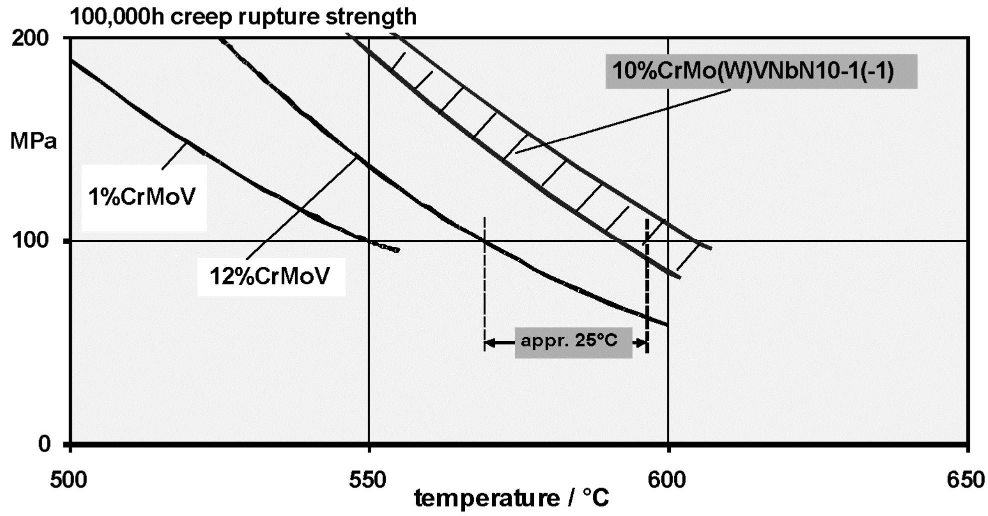

Figure 1 - Creep rupture strength of commonly used forging alloys and advanced 10Cr steels.

Siemens has designed and manufactured 22 high pressure steam turbine rotors using the advanced 10Cr alloyed forging for high temperature service. This is in addition to 33 conventional 12Cr rotors also for higher stressed service components. On these rotors, the journals were welded using a low alloy filler material to prevent wire wooling.

Development of Fabricated Rotors

Small forged components have been used to fabricate larger rotor shafts for many years in Europe. The welded joints were carefully placed in areas of low stress and preferably on larger diameters. As the average rotor size increased, fabrication technology became even more important. As service temperatures increased and newer alloys became more prevalent, fabrication was an excellent way to utilize the best properties of different alloys along the rotor body according to need.

Temperatures and pressures have continued to increase in turbine designs over the years. With the need to minimize capital and operating costs, it became obvious that reducing the number of cylinders would help mitigate expense. However, a single cylinder design requires a single rotor shaft having good creep properties, combined with strength toughness. A single alloy forging cannot meet both the high and low temperature requirements.

In the late 1980s Siemens began development, and in 1990 a patent was issued for a high temperature - low temperature welded rotor.[1] For this design, a 3.5NiCrMoV forging was selected for its strength and toughness and CrMoV was selected for the superior creep life and

[1] U. S. Patent 4,962,586 by Clark, Novak, and Amos, dated 1990.

creep strength. The two forgings were fabricated and welded to make a single rotor shaft. Since the late 90s, over 25 fabricated rotors have been put into operation using this design.

Evolution of Advanced 10Cr Fabricated Rotors

It is a fact from thermodynamics that higher steam inlet temperatures would lead to increased operation efficiencies. Steels for supercritical conditions were developed by the European COST 501 programme, capable of operation at 600°C (1112°F). The material of choice for an elevated temperature operation is X12CrMo(W)VNb10-1-1, or advanced 10Cr. The former COST 522, now COST 536, collaborative programme is continuing the development of the new 10 Cr steels for temperatures up to 650°C. However, for excellent yield strength and toughness in areas of lower steam temperature, the 3.5NiCrMoV forging is the material of choice. A fabricated rotor with the advanced 10Cr in the high temperature section and the 3.5NiCrMoV forging in the lower temperature section yields the optimum composite rotor.

In 1999 the Department of Trade and Industry (DTI, U.K.) awarded a grant to the Parsons Group of Siemens to develop welding and heat treatment technology for the advanced 10 Cr rotor. The challenges were in the large dissimilarity in chemical compositions of the two forging materials and the problems associated with welding metallurgy and postweld heat treatment. Further developmental funding was provided by Siemens Muelheim/Germany and additional support gained from Westinghouse (now Siemens Power Generation) in Charlotte/USA. The programme included collaboration with the University of Cambridge, UK.

The programme was originally scheduled to conclude in 3 years. It was recognized early in the planning phases that the development time had to be minimized. In particular, it was necessary to develop a welding alloy (filler metal) which, with appropriate procedures, would be suitable for joining the dissimilar metals and yet would survive a complex series of post-weld heat treatments. To do this, a decision was taken to avoid a large number of experiments to find a suitable weld metal by taking maximum advantage of theoretical work on alloy design. Two kinds of models were developed for this purpose.

The first involved neural network analysis of a vast database on weld metal properties, including those relevant for power plant applications. A neural network is a highly flexible non-linear regression method which can be enhanced to avoid overfitting, and in a Bayesian framework to indicate the uncertainties of extrapolation. It also does not require any *a priori* assumptions about the functional relationship between the inputs and output. The technique has been fully described elsewhere [3,4], suffice it to say that neural network models were developed to include as inputs the full chemical composition (C, Mn, Si, Ni, Mo, Cr, V, S, P, Cu, Co, W, Ti, Nb, B), the welding heat input, preheat or interpass temperature and the post-weld heat treatment and time. The outputs consisted of the yield and ultimate tensile strengths.

It was also necessary to estimate the hardness of the 3.5NiCrMoV and advanced 10 Cr steels as a function of the pre- and post-weld heat treatments in order to define a viable processing scheme. To do this, a set of experiments in which samples of the steels were quenched and tempered over a well-defined range of temperatures and times were carried out and hardness values measured. The data were then expressed in the form of an Avrami type equation, modeled using a neural network. This work was important in two respects, first in deciding on heat treatments which would not overtemper the 3.5NiCrMoV steel and yet be of sufficient thermal power to anneal the critical areas of the 10 Cr steel. The upper limit to the heat treatment temperatures was determined by the need to avoid the formation of austenite – the Ac1 temperature of 3.5NiCrMoV is much lower than that of the 10 Cr alloy.

A series of weld tests were made and actual results are plotted and shown in Figure 2, showing reasonable agreement between the measured and calculated properties.

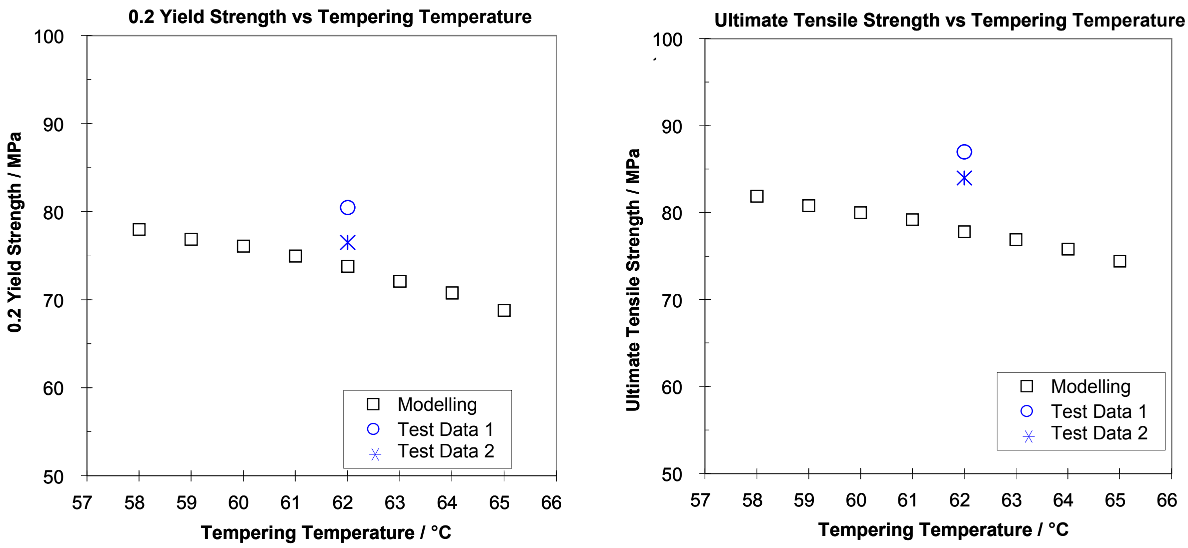

Figure 2 - Comparison of actual weld test results plotted against the range predicted by neural network for weld material development.

After a filler metal was selected and tested using test-blocks, a prototypical or scaled "mock-up" was utilized to further evaluate the mechanical properties. It was important to verify that the soundness and mechanical properties achieved on a large component were at least equal to laboratory weld-test pieces. To evaluate different boundary conditions of fabrication, Muelheim, Germany made an additional scaled mock-up with a slightly different groove opening.

Testing programme

The materials properties requirements for the fabricated high-temperature, low-temperature rotor are thorough as well as rigorous. For the low pressure side, high tensile strength is needed as well as excellent toughness. The material must be resistant to pitting, stress corrosion cracking, as well as high cycle corrosion fatigue. And, low cycle fatigue properties are important to assure a high crack resistance. For the high pressure or intermediate pressure side, creep life and strength are critical as well as thermal fatigue.

The testing programme for the fabricated rotor included the weld metal and the heat affected zones of both the 3.5NiCrMoV forging and the advanced 10 Cr forging. The following nondestructive and mechanical tests were completed and are summarized herein:

- Nondestructive testing – all of the test blocks and mockup components were ultrasonically tested to a reporting level of 50% of a 1.6 mm diameter flat bottom hole standard. There were no reportable problems in any of the test blocks or mockups.

- Metallography – as seen in Figure 6, there were no imperfections or defects. A uniform and regular bead pattern is shown with smooth sidewall profiles in both parent materials. The weld exhibited good root fusion and proper capping bead profile. A high degree of refinement in both weld metal and heat affected zones is the result of good welding parameters and proper bead sequence.

- Hardness – Vickers hardness traverses were conducted across the full width of the weldment at the bottom, mid-section and upper position as shown in Figure 7. The weld metal hardness roughly corresponds to the hardness value of both HAZ's. The weld metal hardness is slightly higher than both base metals because it has higher strength as shown in Figure 8.

- Tensile tests at room and elevated temperature – As shown in Figure 8, the all-weld metal specimens had superior strength to the cross-weld specimens which included weld, both HAZ's and one each of the base metals. All cross-weld specimens broke in one or the other base metal again showing that the weld metal had higher strength.

- High cycle fatigue (HCF) testing – tests were conducted at 20°C and 370°C for cross-weld samples. The cyclical frequencies and stress ratios were specified by materials engineering based on design requirements. All tests at 20°C broke in the 3.5NiCrMoV parent material and all the tests at 370°C broke in the 10 Cr parent material.

- Low cycle fatigue (LCF) testing – cross-weld samples at 20°C were tested at a specified stress ratio with various strain amplitudes as specified by materials engineering. The cycles-to-failure exceeded engineering requirements.

- Chemistry – The weld metal showed consistency from top to bottom and a small amount of dilution from the parent materials.

- Fracture Appearance Transition Temperature (FATT) tests – curves were established for the 10 Cr Rotor parent material, the 10 Cr fusion line and weld metal. The HAZ's of both base metals were tested as well as the fusion line, from -100°C to +100°C. The toughness of the fusion line in the most critical area exceeds 80 Joules (59 ft. lbs.). Both the weld metal and the fusion line results were better than the 10 Cr parent material.

- Creep Testing – Creep rupture testing was conducted on cross-weld specimens at 400°C at various stress levels as specified by materials engineering. All of the results met or exceeded design engineering requirements.

- Residual Stress Measurement – Residual stress was measured by the center hole drill method with strain gauges located in both parent materials, weld metal, and the both HAZ's, before and after postweld heat treatment. The results showed that the levels and patterns of stress were acceptable and consistent with previous fabricated rotors.

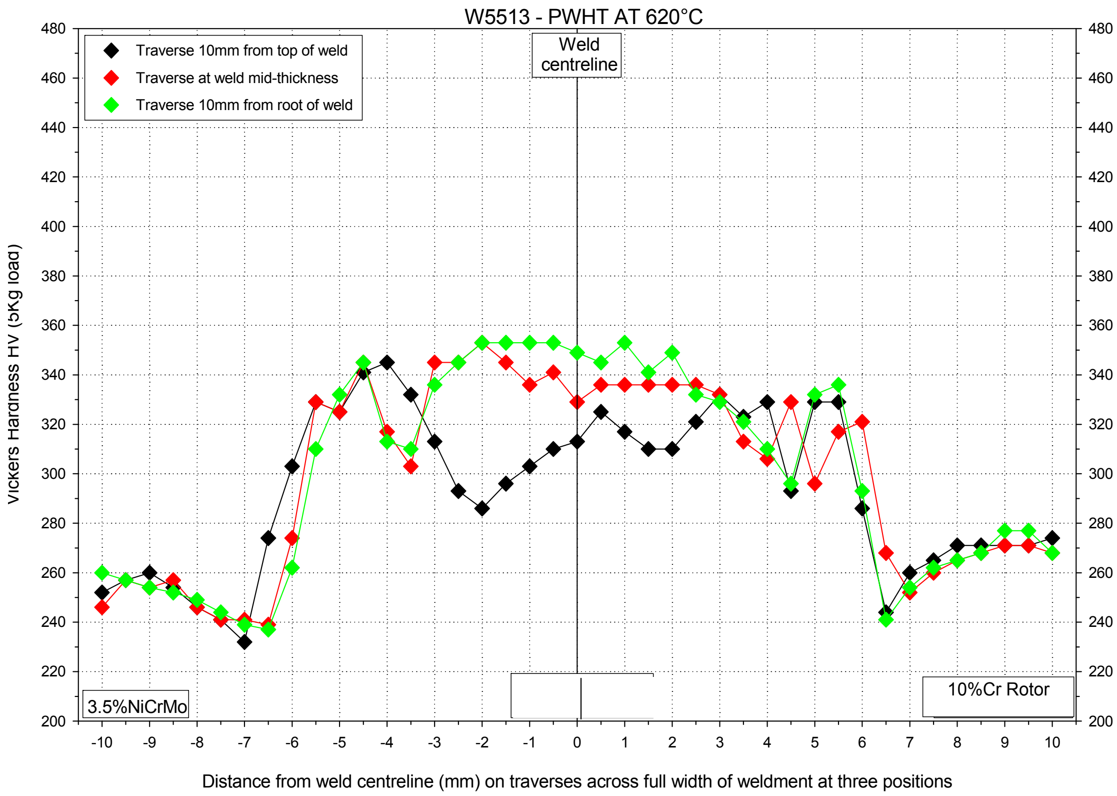

Figure 5 - Hardness survey across base metals, both HAZ's, and weld metal, on large-scale narrow groove GTAW Butt Joint.

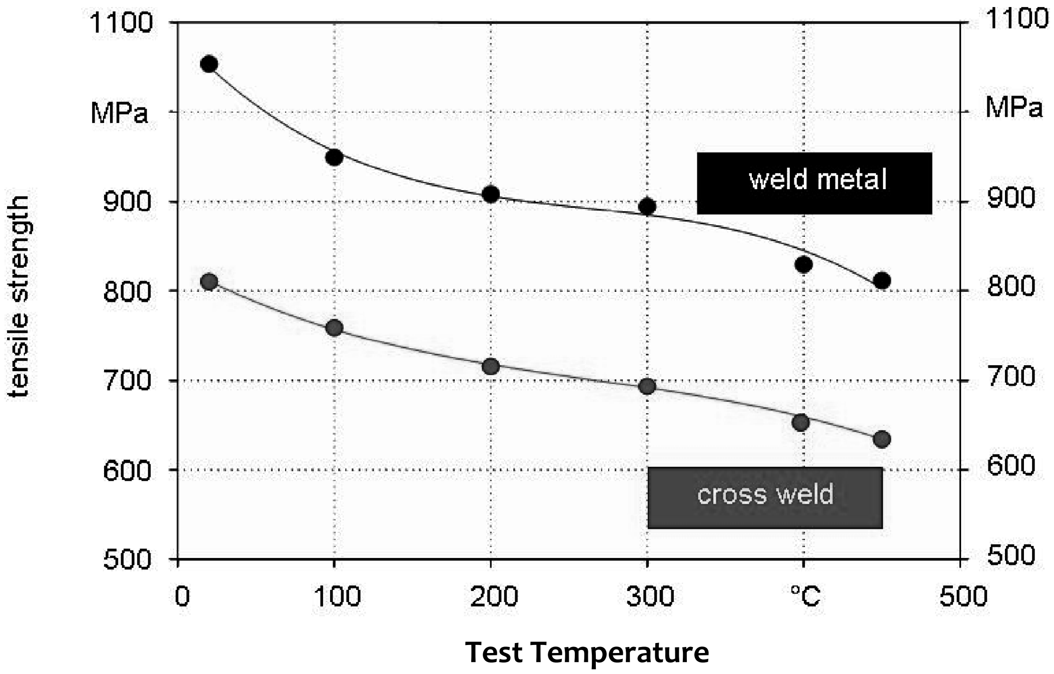

Figure 6 – Narrow groove GTAW butt joint comparative tensile strength of weld metal and cross-weld specimens.

In summary, following a comprehensive modelling programme and complementary testing and examination by Siemens Power Generation and the University of Cambridge, a welding and heat treatment procedure was developed and successfully tested on 2 large mockups. Following a through testing program, all mechanical and metallurgical assessments of these welds showed that the weldment properties matched or exceeded the requirements of the original parent materials. Thus, the results confirmed that all objectives of the project were satisfied.

Application of New Technology to Service Upgrades

A utility approached Siemens concerning high cycle fatigue cracking they had experienced on 1 of their 6 intermediate pressure rotors of similar design. The six rotors were operated in 4 super critical fossil fired units of early 1970's vintage (1 rotor for each unit and 2 spare rotors). These intermediate pressure rotors are also known as second reheat rotors, with an inlet steam temperature of 1050°F. These rotors were originally manufactured from conventional (non-optimized) 10.5Cr material with shrunk-on, low alloy journal sleeves and couplings on each end. The function of the journal sleeves was to prevent wire wooling of the journals. The couplings were the shrunk-on design to allow installation of the journal sleeves. The cracking in the subject rotor occurred under the shrunk-on coupling at the turbine end of the rotor. This was the second of the 6 rotors to experience cracking in this location. The first incident occurred in 1979 and was repaired by the OEM welding on a new shaft end, retaining the shrunk-on construction configuration. The customer reported that the cause of cracking on the first rotor was rotating bending combined with fretting at the interface between the shrunk-on coupling and the shaft.

For the repair of this second cracked rotor, the customer wanted a solution to repair the shaft cracking and eliminate the shrunk-on components from each end of the shaft. The customer also required a solution that would provide increased resistance to high cycle fatigue to eliminate the potential for future cracking. The intent was to develop a repair for this cracked rotor that could be applied proactively to the other similar rotors.

The customer proposed welding on new shaft ends made from CrMoV. While this alloy would have eliminated the wire wooling problem, it was not the best choice for resistance to HCF. The Siemens recommendation was to machine off the existing shafts ends inboard of both journals and weld on new shaft ends to provide a fully integral rotor as shown in Figure 9. Siemens recommended the 3.5NiCrMoV material in lieu of the CrMoV for the following reasons:

- Superior yield and tensile strength
- Increased HCF life and strength
- Excellent toughness
- Higher Cr content which resists C migration
- Creep not a concern at the operating temperature of the shaft end

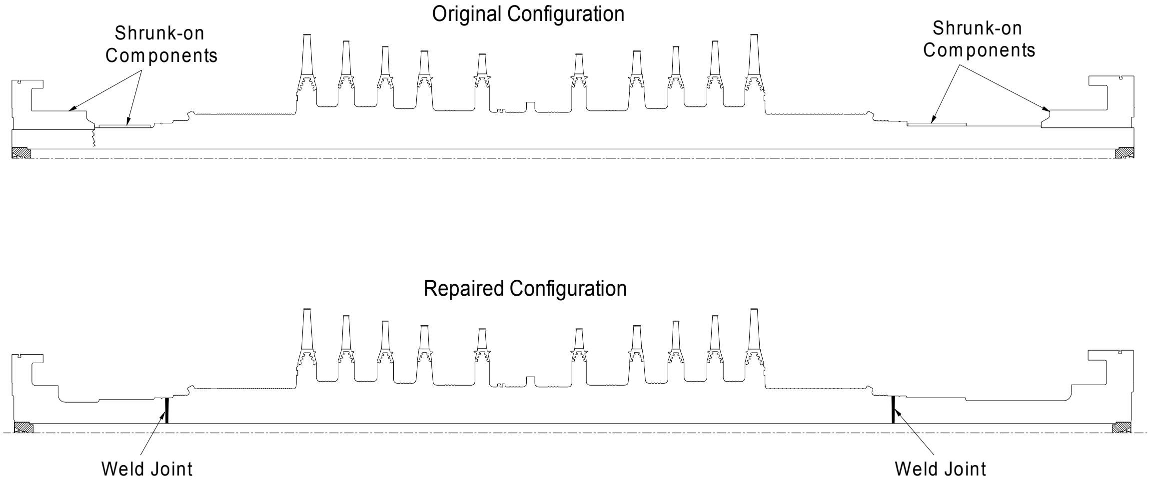

Figure 7 - Rotor Configuration.

As a result of excellent materials property data from the study, the customer agreed to the choice of the 3.5NiCrMoV material for the replacement shaft ends. The first rotor arrived in Charlotte in 2004, with replacement shaft end forgings already procured. Since the rotor was not a Westinghouse or Siemens design, a complete lathe charting was performed as a critical step in designing the repair.

A finite element analysis was performed to determine the residual stresses arising from joining materials with different coefficients of thermal expansion and to determine the operating stresses due to inertial loads. A complete analysis of the weld joint was performed including these stresses as well as steady state and short circuit torque and lateral bending.

Lateral and torsional analyses were performed on the entire turbine train to verify that the change to a fully integral rotor configuration would not adversely affect the dynamic response of the rotor system.

Metallurgical samples were removed from the rotor to confirm the chemistry and mechanical properties of the rotor.

The weld process and custom alloy filler material developed in the research programme were used for the repair. The first end was removed and a new forging was narrow groove welded to the reheat rotor body. This process was repeated on the opposite end. Each weld was ultrasonically tested (UT) to the same requirements as for new forgings. The weldment was then magnetic particle tested (MT). After successful testing, the part was heat treated using the parameters established in the research program.

Following heat treatment, the final UT was performed as shown in figure 10. After all machining operations were completed, the final MT inspection was performed. The rotor was then balanced in the vacuum bunker facility, both at the rated 3600 RPM and at 10% over-speed.

The repair was successfully completed, and the rotor has been returned to service. The third in the set of 6 rotors has been proactively upgraded to the new configuration.

Upgrade Summary

- Advanced technology from a 3 year testing programme for new fabricated rotors was successfully applied to 30+ year old rotors.
- Shrunk-on parts with a geometry associated with previous failures were eliminated.
- The new shaft ends have increased high cycle fatigue resistance due to increased material fatigue strength and improved geometry.
- A repair was provided that is good for the life of the rotor with no operating restrictions.
- A viable repair option for similar 10 Cr rotors was developed.

Acknowledgments

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