

# APPLICATION OF REPAIRS TO TURBOMACHINERY EQUIPMENT IN OIL REFINERY, CHEMICAL, AND POWER GENERATION PLANTS

by

**Phillip Dowson**

General Manager Materials Engineering

and

**David Dowson**

Service Engineer (Repairs)

The Elliott Group

Jeannette, Pennsylvania



*Phillip Dowson is General Manager, Materials Engineering, with The Elliott Group, in Jeannette, Pennsylvania. He has 38 years of experience in the turbomachinery industry. Mr. Dowson is responsible for the metallurgical and welding engineering for the various Elliott product lines within the company. He is the author/coauthor of a number of technical articles, related to topics such as abradable seals, high temperature corrosion, fracture mechanics, and welding/brazing of impellers, and has been awarded numerous patents.*

*Mr. Dowson graduated from Newcastle Polytechnic in Metallurgy and did his postgraduate work (M.S. degree) in Welding Engineering. He is a member of ASM, NACE, ASTM, and TWI.*

---



*David Dowson is a Service Engineer (Repairs) with the Elliott Group, in Jeannette, Pennsylvania. He has been involved with material related failure analysis, repairs to rotating and nonrotating equipment, and aftermarket support.*

*Mr. Dowson received his B.S. degree (2003) from the University of Pittsburgh.*

---

## ABSTRACT

In today's marketplace the repairs of various components especially long lead items for turbomachinery equipment are an important factor for the maintaining reliability and performance of the equipment. This paper will describe repairs applied to compressors and steam turbines.

Various types of repairs will be discussed and how they are applied to rotors, stationary components such as diaphragms and casings. The repairs will be applied to various scenarios that the components have been subjected to. The areas covered will be:

- Mechanical damage caused by rub of rotor on shaft/diaphragm.
- Foreign object damage.
- Erosion caused by either solid particle or liquid.
- Fretting damage.
- Fatigue.
- Creep.
- Corrosion.

Also a review and understanding of the damage mechanisms and what analysis and/or nondestructive testing (NDT) method can be applied to quantify the damage and maintain the reliability of the repair. Various methods will be discussed to assess the damage mechanisms and how to evaluate the extent of the damage so one can assess whether a repair is necessary or the component can function as an as-in condition. Types of repair methods that will be discussed are weld repairs, application of sprayed coating, mechanical fixes, electroless/electrolytic type coating and metal stitching type fixes. The repair methods applied are design process procedures utilizing a design for fitness for service approach.

## INTRODUCTION

In today's marketplace the repairs of various components especially long lead components for turbomachinery equipment are an important factor for maintaining reliability and performance of the equipment. Over the years original equipment manufacturers (OEMs) have developed proven repair procedures for application to these long lead items such as casings, shafts, diaphragms, blades, impellers, etc. Most OEMs are continuously developing and reviewing new ways to repair components to reduce costs and/or delivery time in order to remain competitive. Since downtime of rotating equipment can be costly to the end user, OEMs have developed design proven repair procedures utilizing a design fitness for service approach.

This paper will describe repairs applied to centrifugal compressors and steam turbines. The repairs of components that will be discussed will be rotors, stationary components such as diaphragms and casings. For repairing these components, one must understand the cause of the failure and consequently apply a repair procedure that will address the failed scenario. The various failed scenarios that will be covered are:

- Mechanical damage caused by rub of rotor on shaft/diaphragm.
- Foreign object damage.
- Erosion caused by either solid particle or liquid.
- Fretting damage.
- Fatigue.
- Creep.
- Corrosion.

## CENTRIFUGAL COMPRESSORS

### *Casings*

Generally repairs to compressor casings are mainly due to issues related to erosion/corrosion or mechanical damage. In some cases especially with 30+ year old units that are cast compressor components inherent defects such as shrinkage can propagate with

time to the surface. These defects have to be evaluated and if necessary repaired to a tolerant defect size. This analysis is performed by utilizing fracture mechanics.

The materials for compressor casings have not changed over the past 30 years. The specifications of OEM have refined the chemistry to obtain cleaner materials, improvement in toughness and improvement in reducing the embrittlement effect. Table 1 shows the specifications for compressor casings.

Table 1. Shows the Specifications for Compressor Casings.

ASTM	Trade name	Min. Temperature (°F)
<i>Wrought</i>	Carbon Steel	-50
A516 Gr.60	Carbon-Manganese	-75
A537 C1.1	2.25% Nickel	-100
A203 Gr.A	3.50% Nickel	-150
A203 Gr.E	3.50% Nickel	-160
A353/A553	9% Nickel	-320
<i>Cast</i>		
A216 Gr.WRB	Carbon Steel	-20
A352 Gr.LCB	Carbon Steel	-50
A352 Gr.LC2	2.25% Nickel	-100
A352 Gr.LC3	3.50% Nickel	-150
A352 Gr.LC4	4.50% Nickel	-175
A571	Aust. Nickel Duct. Iron	-320

All OEMs perform repairs to casings utilizing welding procedure specifications that have been qualified. In most cases the weld repairs are performed without a post weld heat treatment to maintain dimensional tolerances. If a post weld heat treatment is needed generally both halves of the casing are bolted together with dummy diaphragms placed inside and dummy end plates to minimize axial movement. This type of heat treatment procedure has been performed to correct a compressor casing defect and has been able to obtain satisfactory dimensional acceptance. Over the past 10 years other techniques have been developed by OEMs to address repairs utilizing welding and not performing a post weld heat treatment. One of the techniques is called temper bead technique.

Temper bead welding refers to a specific welding approach in which the heat of deposited weld layers is controlled so that sufficient heat is produced to temper each previously deposited weld layer. Welding heat is directed to the heat-affected zone (HAZ) and will produce requisite strength and toughness properties without the need for any high temperature post weld heat treatment. The approach employs two or more weld layers applied consecutively to generate both weld and HAZ properties that are equal or superior to the base metal. The technique is applicable to a variety of carbon and low alloy steel materials. In addition temper bead repairs are permitted using gas tungsten arc welding (GTAW) methods. The shielded metal arc welding (SMAW) method minimizes the depth of the base material HAZ by applying small 3/32 inch diameter electrodes for the initial layer. The next layer is applied with 1/8 inch diameter electrodes and the third and succeeding layer are applied using 1/8 inch and 5/32 inch diameter electrodes. Different companies may vary the sequential pattern but the overall intent is to minimize penetration of the initial layer and follow with a layer deposited using a larger diameter electrode so that a higher heat input would be generated. This sequence provides the heat necessary for tempering brittle transformation products in the weld HAZ. The HAZ toughness produced will be equal or superior to the substrate material because the cooling rate of the base material at the fusion line is much faster than the original cooling rate of the base material. This produces a superior microstructure that upon tempering exhibits toughness that is typically superior to the original base material. A key component to evaluate for carbon and low alloy steels temper bead application is the HAZ hardness. However although hardness is examined it is

considered less important in non H<sub>2</sub>S environments because an acceptable toughness implies a defined capacity to sustain deformation in a cracked body without crack extension. Data shown in Table 2 for carbon and low alloy steels demonstrates the beneficial results obtained.

Table 2. Tabulation of Test Data Used in the HAZ Toughness Evaluation.

Study No.	Welding Position	CE	Base Metal (Avg.)		HAZ (avg)		HAZ/BM Ratio	Test Temp (F)	Condition	Base Material <sup>2</sup>	Weld Metal
			R-lb	MLE	R-lb	MLE					
A1	3G	0.58	71	43.3	109	63.8	1.54	30	no grinding	533-B-1	E8018-C3
A2	3G	0.58	71	43.3	96	57.3	1.35	30	With grinding	533-B-1	E8018-C3
B1	1G	0.46	54	31.6	86	66.3	1.59	0	no grinding	516/70	E7018
B2	1G	0.46	58	21.3	48	31.3	1.21	0	With grinding	516/70	E7018
C1	1G	0.59	77	49.3	110	68.7	1.43	-4	no grinding	508-2	E309L*
C2	1G	0.59	77	49.3	114	66.3	1.48	-4	no grinding	508-2	E309L*
C3	1G	0.59	77	49.3	121	71	1.57	-4	no grinding	508-2	E309L*
C4	1G	0.59	77	49.3	115	72	1.49	-4	no grinding	508-2	E309L*
D1	1G	0.67	n/a	n/a	117	n/a	1.75	32	no grinding	P11	E8018-B2L
D2	1G	0.67	n/a	n/a	109	n/a	2.27	-40	no grinding	P11	E8018-B2L
D3	1G	0.65	n/a	n/a	60	n/a	1.71	-80	no grinding	P11	E8018-B2L
E1	1G	0.9	112	n/a	120	n/a	1.07	32	no grinding	P22	E9018-B3
E2	1G	0.9	74	n/a	82	n/a	1.11	-40	no grinding	P22	E9018-B3
E3	1G	0.9	14	n/a	52	n/a	3.71	-80	no grinding	P22	E9018-B3
F	5G	0.69	91	30.0	54	43.0	1.74	68	no grinding	217WC6	E8018-B2
G	5G	1.29	30.0	32	30.0	1.10	68	no grinding	217WC9	E9018-B3	
H	1G	0.63	125 <sup>1</sup>	79.0	125	92.0	1.00	RT	no grinding	387-B	E8018-B2
I	1G	0.93	125 <sup>1</sup>	77.0	125	98.0	1.00	RT	no grinding	217WC9	E9018-B3
J	5G	0.68	32 <sup>1</sup>	33.0	73	59.2	2.28	RT	no grinding	P4	E8018-B2
K	5G	0.88	90 <sup>1</sup>	82.0	139	83.0	1.54	RT	no grinding	P5	E9018-B3
L	5G	0.88	81 <sup>1</sup>	66.0	68	62.3	1.33	RT	no grinding	P5	E9018-B3

Note:

- 125 R-lbs represents machine limits.
- Service Aged - 244,000 hours.
- Service Aged - 161,000 hours.
- Service Aged - 244,000 hours.
- All materials used in this study represent material heats fabricated prior to 1980 with the exception of those identified as Study No. B & C.
- 1<sup>st</sup> layer E309L, 2<sup>nd</sup> & subsequent layers—E308L.

Legend:

- A1, A2 - Ontario Power Generation  
 B1, B2 - Alliant Energy Corp.  
 C1, C2, C3, C4 - Electricite de France  
 D1, D2, D3 - PVRC P4  
 E1, E2, E3 - PVRC P5A  
 F - EPRI P4 Casting  
 G - EPRI P5A Casting  
 H - TU Electric P1/P4  
 I - TU Electric P1/P5  
 J - EPRI Service Aged P4  
 K, L - EPRI Service Aged P5A

The hardenability for different low alloy steel composition was measured numerically by computing the carbon equivalent based upon the base metal compositions. Additionally the average HAZ Charpy V-notch impact toughness was normalized to the average base metal toughness. By using this method the effects of different test temperatures would be minimized. A tabulation of these data of HAZ/BM ratio against carbon equivalent are shown in Figure 1 (Gandy and Smith, 2001).

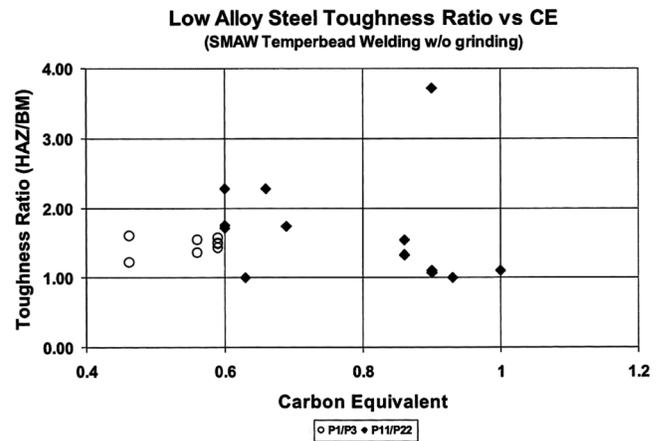


Figure 1. Effect of C.E. Value on Low Alloy Steel Toughness Ratio for SMAW Temperbead Welds (No Grinding).

From these results all of the toughness ratios are greater than unity 1. This indicates that the HAZ toughness is greater than that measured for the base metal (at the same temperature) for a grade range of carbon equivalent. The range of carbon equivalency extends from P1 through P5 materials. This temper bead technique can be applied successfully without interlayer grinding and without high temperature post weld heat treatment (PWHT). This method becomes very important for materials such as ASTM A516 Grade 60 and ASTM 203 grades, which operate at temperatures as low as -175°F (-115°C).

API RP 945 states that limiting hardness alone will not prevent stress corrosion cracking and therefore residual stresses need to be addressed. Consequently the application of the temper bead

technique becomes an alternative acceptable approach to high temperature PWHT. (Refer to ASME code rules for the application of temper bead welding, RRAC code development activities, EPRI Charlotte, NC 2003 1002943.)

Although carbon and low alloy steels have had approved weld repair procedures by all OEMs, successful qualified repair procedures of nodular or flake graphite cast iron is not as straightforward compared to steel. Minor weld repairs have been done successfully by SMAW using nickel and nickel-iron electrodes. Nodular cast iron especially the ferritic grades have more ductility as compared to cast iron and therefore can take the contraction and hardening during the welding process. For flake cast iron there is no give and therefore the contraction and hardenability can lead to cracking. The authors' company has procedures for welding both nodular and cast iron with preheats below 800°F (427°C). Other welding methods for cast iron are with preheats greater than 1300°F (704°C) for fusion welding using a cast iron filler rod using oxyacetylene welding.

Another technique is called metal stitching. This process has been applied successfully to damaged cast iron compressor casings (Figure 2), steam turbine exhaust casings and stationary components such as bearing housing and diaphragms. Metal Stitching is a cast iron repair process that does not require the use of heat such as in welding. The advantage of no heat being added is it reduces the chances of part distortion. Metal stitching is a mechanical fix that leaves the cast iron physically and metallurgically unaffected.



Figure 2. Shows an Air Compressor Casing That Has Cracked During Service.

Holes are drilled perpendicular to the fracture and milled out in the form of the metal stitching fasteners. The fasteners, which are made of high strength nickel alloys, are inserted until the milled slot is completely filled. Each fastener is preloaded by peening, which increases its tensile strength and ensures proper bonding of the material. Holes are drilled into the fracture itself and metal studs are inserted (Figures 3 and 4). The studs overlap one another, which completely fill the fracture with new material. Finally, the fracture area is machined to a smooth finish (Figure 5).

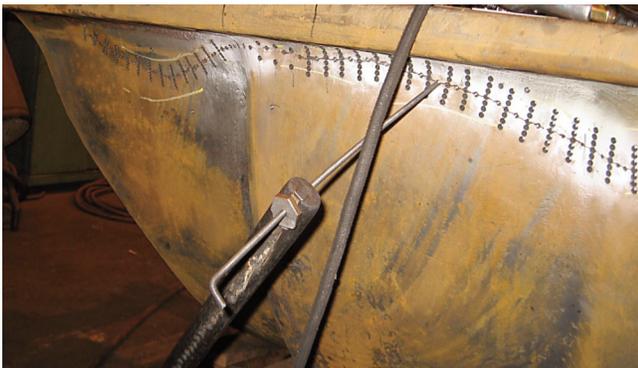


Figure 3. Holes Are Drilled Perpendicular to the Fracture Following a Specific Spacing Pattern.



Figure 4. Shows Studs/Dowels Peened and Any Excess Material Is Removed.



Figure 5. Shows Repaired Casing Ready for Service.

Repair by metal stitching, when applicable, is a viable alternative to welding. Welding can introduce thermal stresses and cause distortion. Metal stitching is a cold process that does not introduce any stresses in the repaired equipment. Repairs can be performed onsite without major disassembly of equipment components. This increases the speed of the repair and reduces losses due to production downtime. The weld repair of cast iron is never a guarantee, which makes metal stitching a more reliable alternative.

Metal stitching is a relatively cheap and reliable alternative to welding cast iron. Unlike welding it requires no preheat and introduces no thermal stresses or distortions. Metal stitching may be performed without major disassembly of equipment components and avoids the cost and leadtime replacing expensive castings. Repairs can be made onsite thereby saving production downtime. Results of this cold process produces a permanent repair with 100 percent joint efficiency in cast iron.

As stated before since ductile cast iron has predominately a ferritic matrix and therefore is capable of local plastic deformation to accommodate these welding stresses and is therefore better suited to absorb welding stresses as compared to flake cast iron. Generally depending on the size of the weld repair either Ni base or a combination of Ni base and Ni-Fe base are used. The AWS classifications for the electrodes are A515 class E Ni-CI and A515 class E NiFe-CI.

Some procedures may require peening of each weld pass while still hot to reduce shrinkage stresses. The peening should be done with repeated moderate blows using a round nose tool and sufficient force to deform the weld metal but without rupturing it. Effective peening stretches the weld metal to help compensate for the shrinkage that occurs during cooling. The peened metal is allowed to cool before another bead is deposited near it. By using a low welding current, a small diameter electrode and depositing multiple narrow beads only the lower level layer weld metal has a high carbon content. Subsequent layers of weld metal level to temper and reduce hardness of the first layer. Complete flux

removal is essential after each weld pass before depositing further weld metal since entrapped slag can impair the strength properties of the weld. Preheat may be applied to prevent cold cracking, reduce hardness in the HAZ, reduce residual stresses and reduce distortion. Satisfactory repair processes have been developed for both with and without preheat.

### COMPRESSOR SHAFTS

Throughout the last 20 years hundreds of shafts have been successfully weld repaired by the authors' company and to date are operating as designed. This success rate can be attributed to the analytical approach that has been developed over the years to assume that the weld repair will function as good as or better than the original configuration. This approach was required intensively to satisfy a defect tolerant design concept and safety considerations. Also it was necessary to overcome the initial reluctance of the equipment owners and their insurers, who have now embraced this technique as a way of reducing financial and technical exposure when there is a rotor malfunction.

Fundamental to any repair is in knowing the cause of failure before establishing repair procedures to ensure it does not reoccur. In general all OEMs have processes and standard restoration specifications that act as guides to assure all initial areas are addressed prior to the actual repair being initiated. Some of the tools utilized to determine the root cause of the failure and the condition of the base metal include nondestructive testing, metallurgical failure analysis, mechanical property testing, chemistry analysis, stress analysis using finite element methodology, frequency and model testing, fracture mechanics methodology and other tools as needed.

#### Mechanical Inspection

This is required to check if distortion or bowing has occurred that would render the shaft unrepairable or would need to be thermally straightened. This inspection is done with the following test:

- Dimensional
- Concentricity/Runout
- Check balance
- Nondestructive testing (NDT) to evaluate all rotor surfaces for cracking and other defects
- Visual examination to evaluate condition of shaft surfaces especially under areas that have contact to impellers, sleeves, thrust collar, etc. Evidence of fretting in these areas would be a concern and depending on the extent would need to be evaluated for root cause. Where fretting is slight, these areas may be acceptable as is. Other areas where damage to surface is unacceptable will have to be removed and either repaired by nickel/electrolytic type coating or by welding. If a harder surface contact material is required a combination of both can be used.

Generally shafts are manufactured from either rolled bars or forgings and the materials are either AISI 4340 or 4330. These materials can be heat treated to give the required mechanical properties such as strength and toughness down to  $-150^{\circ}\text{F}$  ( $-101^{\circ}\text{C}$ ). Repairs to these shafts are generally done by welding using high strength weld deposits or for repair to shaft journal area using high velocity oxygen fuel (HVOF) thermal spray processes. The coatings utilized are either a tungsten carbide coating or chromium carbide.

For repairs by welding either GTAW or submerged arc welding can be utilized using high strength weld deposits. OEMs have proven repair procedures where they have developed metallurgical and mechanical data utilizing mock ups that are welded using OEM's propriety procedures such as fatigue data, stress corrosion cracking (SCC) data and toughness strength. In determining the required weld initial strength and toughness the OEMs may have to

perform finite element analysis to determine the operating stresses in the vicinity of the repair area. From the finite element analysis (FEA) one can evaluate low cycle fatigue (LCF) initiation analysis and also apply fracture mechanics to look at potential crack propagation assuming a pre-existing semi-elliptical defect at various R ratio. Since the fatigue condition for in-service compressor shafts can involve high mean stresses at the low cyclic stresses. A comparison of the  $\Delta K_{th}$  threshold stress intensity factor range at the higher R ratio (0.7 or greater) is of most interest to the design engineer. Values of  $\Delta K$  at various R ratios and crack depths can be determined. The R value is defined as the ratio of minimum stress to maximum stress ( $R = \sigma(\text{Min})/\sigma(\text{Max})$  in one cycle) (Figure 6).

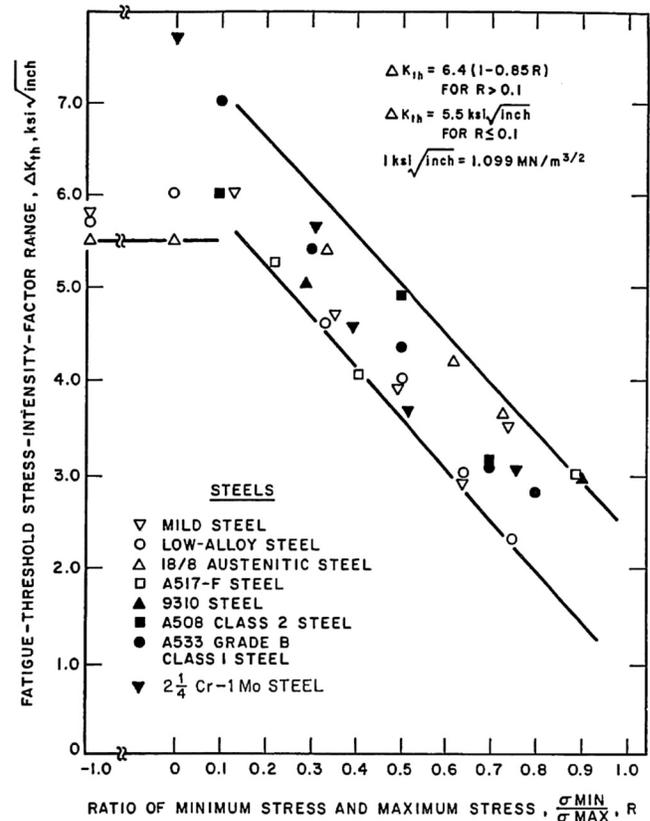


Figure 6. Dependence of Fatigue – Threshold Stress – Intensity Range on Stress Ratio.

When one is evaluating welded rotating repair components one must apply a defect tolerant design concept. Nearly all flux welding processes have inherent indications present that one must account for in the design of the repair. Utilization of fracture mechanics as described previously is utilized in the repair.

All OEMs work very closely with the end user and his internal engineer during the testing and nondestructive testing using magnetic particle (MT) and ultrasonic (UT) of the repaired shaft. Prior to repair of the shaft a MT is performed to ensure no further defects are evident. The NDT is performed before and after PWHT. It should be highlighted that the PWHT of the shaft is performed in a furnace that gives good circulation around the shaft, in other words is supported off the furnace floor. This is to ensure that no instability occurs that can give further problems during operation.

### IMPELLERS

Frequently repairs to impellers are performed where erosion, corrosion or mechanical damage is evident. Where impellers are cracked by fatigue they are mostly replaced with new impellers. Fatigue impellers that have occurred in a short length of time  $< 3$  years are evaluated to determine the source of the cyclic loading.

Impellers that have small fatigue cracks can be weld repaired by removal of the cracks by grinding. NDT of the ground area followed by a weld repair using approved OEM tested procedures. Generally these cracks are either at the leading edge (inlet) or the outside diameter (discharge). Blending of the remaining toes of the fillets to remove any fatigue damage is frequently done.

In welded impeller construction, as shown in Figure 7, the application of fracture mechanics techniques is essential for evaluating the critical flaws in the various regions of the impeller. The most critical flaws are those of category A, which are located at the toe of the fillet. Fluorescent magnetic particle inspection is the technique normally utilized in locating flaws that may affect the integrity of the impeller. Since the NDT inspection technique used has a practical detectable flaw size limit, the engineer must design the impeller to meet this acceptable flaw size.

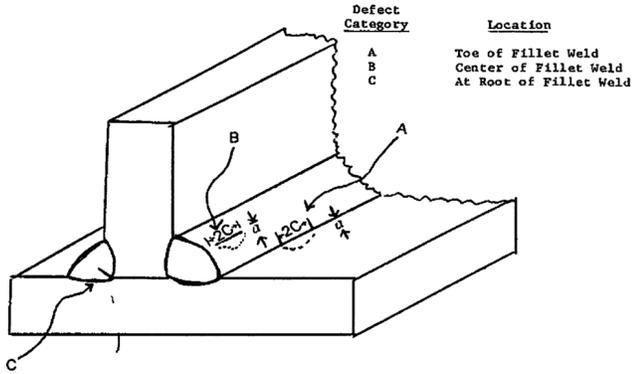


Figure 7. Showing Location of Flaws in a Fillet Welded Impeller Construction.

To determine the critical acceptable flaw size for an impeller, consider the growth of a semi-elliptical surface flaw at the toe of the fillet. By applying the weight function methodology related to weldments, one can obtain an adequate solution for the complex geometry and loading system.

The weight function method is where the stress intensity for any loading system applied to the body can be calculated by integration of the product of the stress field  $\sigma(x)$  and the weight function  $m(x,a)$  (Niu and Glinka, 1989; Shen and Glinka, 1991).

The growth of a surface semi-elliptical crack can be satisfactorily characterized by the extension of it two semi-axes. Consequently, the only two weight functions that need to be derived, i.e., one for the deepest point and the second for the surface point of a semi-elliptical surface crack in the crack front. In modeling the growth of the semi-elliptical cracks, two ranges of  $\Delta K_{IA}$  and  $\Delta K_{IB}$  are calculated ( $\Delta K_{IA}$  corresponds to the deepest point and  $\Delta K_{IB}$ , the weight function (Equation (1)) is utilized with the appropriate functions (Equations (2) and (3)).

$$K_I = \int_0^a \sigma(x)m(x,a)dx \quad (1)$$

and

$$m_{A(a,x)} = \frac{2}{\sqrt{2\pi(a-x)}} \left[ 1 + M_{1A} \left(1 - \frac{x}{a}\right)^{\frac{1}{2}} + M_{2A} \left(1 - \frac{x}{a}\right) + M_{3A} \left(1 - \frac{x}{a}\right)^{\frac{3}{2}} \right] \quad (2)$$

$$m_{B(a,x)} = \frac{2}{\sqrt{\pi x}} \left[ 1 + M_{1B} \left(\frac{x}{a}\right)^{\frac{1}{2}} + M_{2B} \left(\frac{x}{a}\right) + M_{3B} \left(\frac{x}{a}\right)^{\frac{3}{2}} \right] \quad (3)$$

Examples of parameters  $M_{1A}$ ,  $M_{2A}$ ,  $M_{3A}$ ,  $M_{1B}$ ,  $M_{2B}$ , and  $M_{3B}$  for various geometries are given in Shen and Glinka (1991) and in Glinka and Lambert (1993).

Since one is considering a nonpropagating flaw, the  $\Delta K_I$  value (whether  $\Delta K_{IA}$  and  $\Delta K_{IB}$ ) needs to be less than threshold stress intensity  $\Delta K_{TH}$  for the impeller material under investigation. If the impeller design is based upon a 3 mm acceptable surface linear flaw size, then the associated stress intensity factor range is derived by utilizing Equations (1), (2), and (3) to give Equations (4) and (5):

$$\Delta K_{IA} = \int_0^a \Delta\sigma(x) m_A(x,a) dx \quad (4)$$

and

$$\Delta K_{IB} = \int_0^a \Delta\sigma(x) m_B(x,a) dx \quad (5)$$

By applying this methodology, a value  $\Delta K_{IA}$  and  $\Delta K_{IB}$  can be calculated for a flaw, where  $a = 0.125$  inches, at a particular location along the weld toe of the impeller.

Values of  $\Delta K_{TH}$  for impeller materials can either be obtained from the open literature or by generating the fatigue crack growth rate (FCGR) data for the appropriate R. Figure 3 shows typical FCGR for  $R=0.65$  and  $R=0.2$ . Another approach to determine  $\Delta K_{TH}$  is to utilize the expression derived by Barsom and Rolfe (1977). This Equation (6) is valid for martensitic, bainitic, ferritic, pearlitic, and austenitic steels subjected to stress ratios R, greater than 0.1.

$$\Delta K_{TH} = 6.4(1-0.85R) \text{ ksi}\sqrt{\text{in}} \quad (6)$$

The value of  $\Delta K_{TH}$  for  $R < 0.1$  is a constant equal to 5.5 ksi $\sqrt{\text{in}}$ . Since most of the compressor materials are martensitic steels with yield strength of approximately 552 to 689 MPa, Equation (6) can be utilized. For R ratios of 0.2 and 0.65, the calculated  $\Delta K_{TH}$  values are 5.28 ksi $\sqrt{\text{in}}$  and 2.85ksi $\sqrt{\text{in}}$ , respectively.

From the experimental data generated for AISI 403 material by the authors' company (United Technologies Research Center, 1980), the  $\Delta K_{TH}$  for  $R = 0.2$  and 0.72 were 6.8 ksi $\sqrt{\text{in}}$  and 4.2 ksi $\sqrt{\text{in}}$ , respectively.

It should be realized that environmental effects, such as temperature/gas media or relative humidity can affect the  $\Delta K_{TH}$  value. Generally, one should use a conservative  $\Delta K_{TH}$  value when data are not available for the material and environment under review. A conservative  $\Delta K_{TH}$  value of 2.8 ksi $\sqrt{\text{in}}$  is selected. For these cases, the calculated  $\Delta K_{IA}$  and  $\Delta K_{IB}$ , for the 0.125 inches acceptable flaw size has to be less than 2.8 ksi $\sqrt{\text{in}}$  to ensure a nonpropagating fatigue flaw.

Materials, weldments, and associated heat affected zones used for impellers generally have excellent fracture toughness ( $K_{IC}$ ). The critical flaw size associated with the fracture toughness of the material far exceeds the size of a non propagating flaw by fatigue. Consequently, the critical flaw size for fast fracture is extremely large. For impellers that operate in low-temperature environments -150°F (-101°C), materials are selected that give adequate fracture toughness values for both materials and associated weldments. Generally, the  $K_{IC}$  value of the materials is greater than 80 ksi in. Experimental testing of 50 mm thick specimens conforming to specification AISI 4140 material gave a  $K_{IC}$  value of 97 ksi $\sqrt{\text{in}}$  (Pisarski and Davey, Private Report).

## STEAM TURBINES

Generally repairs to steam turbines are mainly due to issues related to erosion/corrosion, stress corrosion cracking, fatigue, creep damage or foreign object damage. The above various damage mechanisms will be reviewed for components such as casings, nozzles and rotors (including blades) and the appropriate method of repair recommended.

### Casings

For steam turbines casing materials can range from ASTM A216 WC13 to ASTM A217 WC 9 (2¼Cr1Mo) (Table 3). Generally

repairs to these materials are done utilizing various welding processes ranging from GTAW, SMAW and flux-cored arc welding (FCAW). When considering repairs to inlet turbine casings that are subjected to temperatures greater than 750°F (399°C) creep rupture has to be considered. For these higher temperatures low alloy steels are utilized for the temperature range up to 1050°F (566°C). The correct designs are ½Cr½ Mo¼V or 2¼Cr1Mo steel material. These materials have been used for the past 50 years. In repairing these materials for older casings replace ductility becomes important. Especially with chemistries that are high in residual elements such as phosphorus, antimony, tin, copper, aluminum and sulfur. All of these materials can be detrimental to reheat cracking especially the ½Cr½ Mo¼V. Special welding procedures have been developed for welding or weld repair of these materials. This embrittlement phenomenon occurs when the casing is held in the temperature range 450°C to 660°C (842°F to 1220°F). This cracking can occur either during service or during the PWHT. However, thermal fatigue is the most common cause of casting cracking and generally occurs on the surface at transitions areas such as nozzles/casing barrel or along the nozzle chest. Repairs are considered after the casing remaining life is evaluated. This is either done by reviewing the history of the casing or performing nondestructive techniques and if necessary destructive tests. These techniques are explained in detail in Dowson, et al. (2005). If the casing has adequate remaining life the following steps are taken for repair.

1. NDT the defects to determine the depth and length. Perform a creep/fatigue life assessment to determine if repair is necessary.
2. Determine what type of defect is present. A fatigue crack, SCC or casting shrinkage defect, etc.
3. If defect unacceptable, then one needs to determine the extent of excavation and the weld repair to be performed.

Table 3. Various Composition of Steels Used for Turbine Casings.

Material	Composition (wt%)										Range of Application °F
	C	Si	Mn	Cr	Mo	V	Ni	Nb	N		
Flake-graphite gray - cast iron	3.00	1.80	0.70	---	---	---	---	---	---	---	752 max
Ferritic SGI	3.22	2.94	0.25	---	---	---	---	---	---	---	---
Carbon Steel	0.20 max	0.50 max	1.10 max	---	---	---	---	---	---	---	---
C-1/2Mo	0.25 max	0.20-0.50	0.50-1.00	---	0.50-0.70	---	---	---	---	---	896 max
Cr-1/2 Mo	0.15 max	0.60 max	0.50-0.80	1.00-1.50	0.45-0.65	---	---	---	---	---	977 max
2 1/4Cr-1Mo	0.15 max	0.45 max	0.40-0.80	2.00-2.75	0.90-1.10	---	---	---	---	---	1000 max
Cr-Mo-V	0.15 max	0.15-0.30	0.40-0.60	0.70-1.20	0.70-1.20	0.25-0.35	---	---	---	---	1049 max
1/2Cr-Mo-V	0.10-0.15	0.45 max	0.40-0.70	0.40-0.60	0.40-0.60	0.22-0.28	---	---	---	---	1049 max
T91	0.08-0.12	---	---	8.0-9.5	0.85-1.05	0.18-0.25	0.4 max	0.04-0.10	0.03-0.07	---	1100 max

Thermal fatigue cracks are generally transgranular and may be concentrated near stressed areas or abrupt changes in section or spread over a large area such as inside surface of the valve steam chest body. These cracks tend to grow slowly and can be found during the 5/6 year inspection cycles before they grow to a critical size, then catastrophic brittle fracture can occur. It is not uncommon to see casings with low cycle fatigue cracks in abrupt changes in sections at the surface. If the casing material has sufficient fracture toughness, the fatigue cracks may never grow to a critical size because they will be arrested well before that due to the decreasing through wall thermal stresses.

Most OEM's have qualified weld procedures for repairing these casings in material ranging from ASTM A216 WC 13 to ASTM A217 WC 9. In casings where a PWHT would be a problem as stated in the compressor section, a temper bead technique procedure would be followed where each operator is qualified for that material with a material of the same carbon equivalent (CE) or greater.

## TURBINE ROTOR

As was stated for compressor shafts in the last 20 years numerous turbine shafts have been successfully repaired by the authors' company and to date are operating as designed. Figure 8 shows the three basic types of repairs used on integral forged rotors:

- Full disk stage rebuild
- Disk rim rebuild
- Shaft journal surfaces

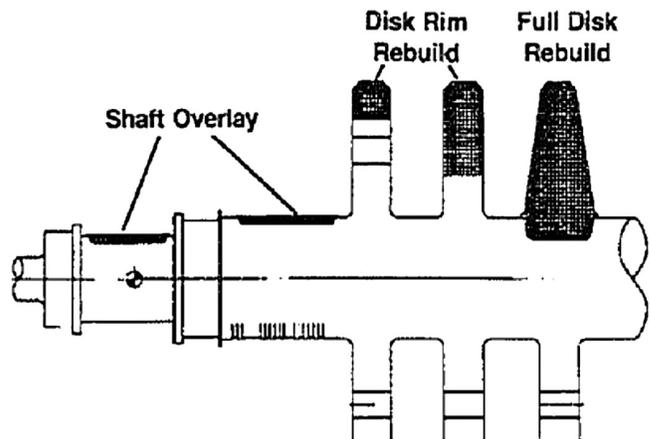


Figure 8. Types of Weld Repairs.

For further details related to the economic and material test data of the rotors refer to references (LaFave, 1991; LaFave and Wiegand, 1994).

## Repairability Assessment and Recognition

Once the cause of the problem is understood and the extent of the damage is quantified, an assessment of the type and complexity of the repair is determined. Although this paper focuses on weld repairs, there are other types of repairs such as mechanical, coatings, plating, etc., which need to be considered to find the best option for each particular case. The best option is one that meets the customer's commercial and technical requirements and carries the lowest possible life cycle cost and relative risk. During the engineering analysis, special enhancements can be applied to the components that can maximize the integrity of the component and, in certain cases, provide performance enhancements.

## Repair Development and Testing

Once the repair is designed and considered feasible, the procedure needs to be developed and tested. Much of the long term metallurgical and mechanical property testing is accomplished proactively on mockups that were welded using company proprietary procedures. These procedures have been developed to cover various component characteristics and unit operating conditions, such as rotor base metal, stage temperatures and operating stresses. This allows for the standardized and proven procedure to be reapplied for similar applications without the need to requalify for each repair. Therefore, once it is shown that the standard filler material will meet the structural and operating criteria of the particular application, there is no need to completely requalify for each individual job. This minimizes the repair cost and repair cycle time without adding any technical risk. To minimize the technical risk and assure a reliable and responsive repair, the authors' company has developed a long term property database for various weldments and heat affected zones. These data include, but are not limited to the following:

- *Room and elevated temperature tensile properties*—Generally performed to determine weld metal yield strength (0.2 percent offset) at various temperatures. This information is correlated with creep rupture test data to determine the allowable stress values that are required by the design engineer (Figure 9).

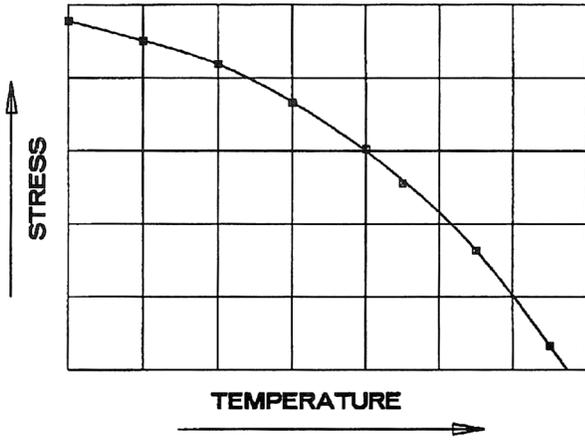


Figure 9. Room and Elevated Temperature Tensile Properties.

• *Impact and fracture appearance transition temperature (FATT) data*—This testing is performed to determine the fracture toughness of the weldments and heat-affected zone of the actual rotor and weld materials (Figure 10).

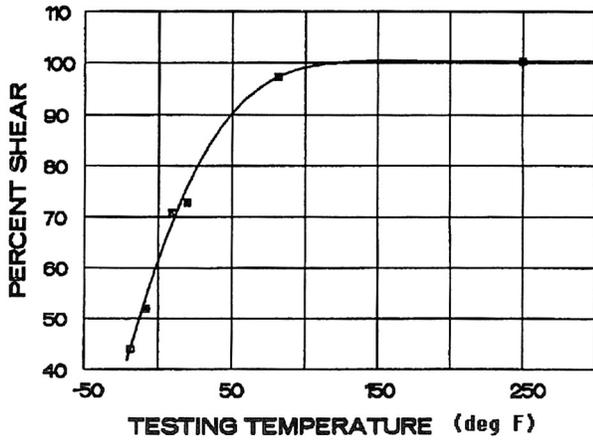


Figure 10. Impact and Fracture Appearance Transition Temperature (FATT) Data.

• *Creep/stress rupture data*—For rotors operating at high temperatures, creep has to be taken into consideration to assure the repaired rotor will operate satisfactorily. Consequently, creep rupture data were generated for various weldments and are shown in a typical Larson-Miller curve (Figure 11).

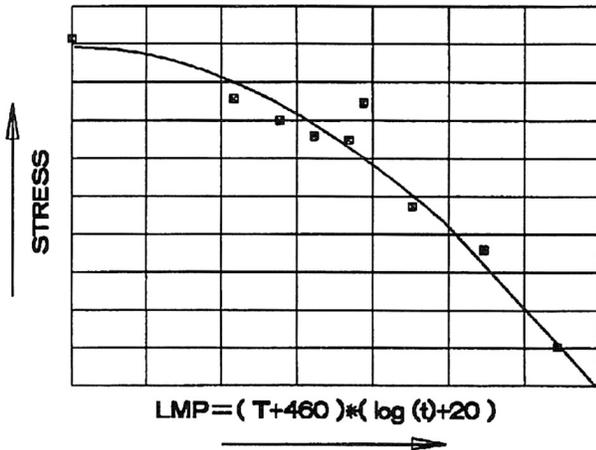


Figure 11. Creep/Stress Rupture Data.

• *Fatigue properties*—Fatigue testing of various mock-up weldments was accomplished to generate S-N curves with fully reversing ( $R = -1$ ) fatigue endurance limit set at  $10^8$  cycles (Figure 12).

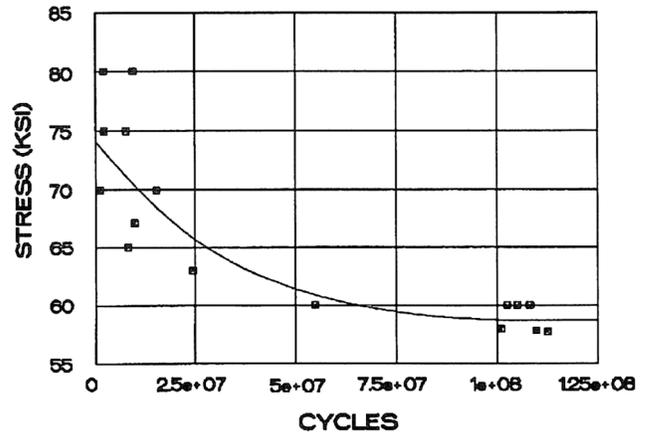


Figure 12. Fatigue Properties.

• *Stress corrosion cracking threshold limits*—In certain environments stress corrosion cracking can occur especially in highly stressed locations. Series of stress corrosion cracking tests were conducted on the weldment rotor base material and associated HAZ using linear elastic fracture mechanics.  $K_{ISCC}$  values were measured for each material/weldment condition (Figure 13). When repairing a turbine rotor that has suffered SCC, the stress intensity  $K_I$  values must be less than the  $K_{ISCC}$  values of the weld deposit and associated HAZ. Also when stress corrosion is known to be a problem, the HAZ of the weld deposit is located in a low stress area. Since the weld metal has a lower yield strength than the HAZ, the  $K_{ISCC}$  value is higher. Consequently, when the  $K_I$  values are high the more resistant  $K_{ISCC}$  weld metal is used.

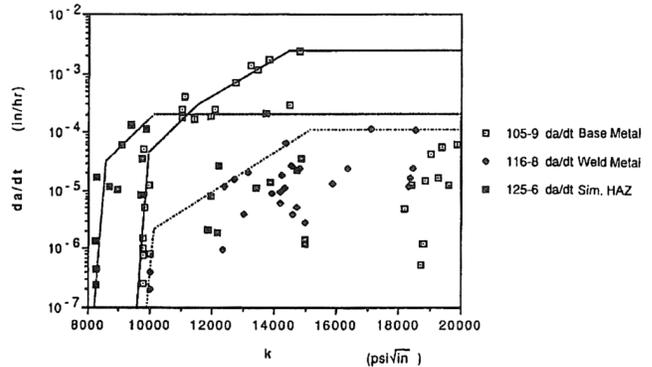


Figure 13. Stress Corrosion Growth Rate as a Function of Stress Intensity for Weld Metal, Heat Affected Zone and Base Material.

These data allow for the weld metal properties to be compared against mechanical analysis results and company design criteria to assure that the proposed repair will be reliable. Shorter term testing, such as weldability, tensile, hardness and toughness, is routinely done on the base metal, weld metal and HAZ for each engineered rotor repair.

*Repair Implementation*

After the repair procedure has been developed and tested, the procedure is initiated using only approved procedures, specialized processing developed for the individual job and trained qualified technicians. This execution phase is as important as the engineering/development phase to assure the rotor repair is successful.

Each part of the aforementioned rotor restoration philosophy is equally important and must be accomplished in their entirety to assure every major repair is successful and without unnecessary risks. The following case study will show how this structured approach is put into practice.

### CASE STUDY—150 MW IP/LP ROTORS

#### Background

Two 13-stage, integrally forged rotors from identical 30 year old turbines, that operated at the conditions shown in Table 4 and located on a western Canadian power plant, were sent to a service shop for repairs (Figure 14). The fifth stage disk rim had cracked at the top pressure land due to high cycle fatigue. It should also be noted that the fifth stage blades also exhibited root cracks and fretting. The root cause of the cracking, as determined by customer consultant, was high vibratory stress due to a second bending mode that was resonant with the nozzle passing frequency. It was recommended that to solve the problem the customer should use a redesigned diaphragm with the number of nozzle openings changed from 62 to 92 to minimize the potential for resonance. To increase the reliability of the disk rim and blades, the blade material was upgraded to 422 SS, the blade root was shot-peened and the blade attachment was reengineered to tighten tolerances and increase fillet radii to reduce stresses and increase the fatigue margin.

Table 4. Showing Operating Conditions.

Speed	3600 rpm
Inlet Pressure	1800 psig
Inlet Temperature	1100°F
Fifth Stage IP Temperature	690°F
Discharge Pressure	1.5 HgA

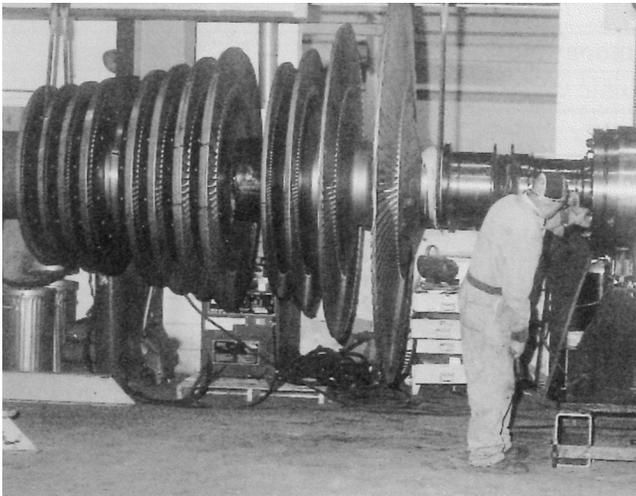


Figure 14. 13-Stage IP/LP Rotor.

With good understanding of the root cause of the cracking and recommended corrective action in place, it was required to repair the disk rim of the fifth stage and assure that the repair would function reliably.

#### Testing and Qualification

The service shop worked very closely with the customer and his internal metallurgical consultant during this phase. The first step was to nondestructively test, using the magnetic particle and ultrasonic techniques to confirm and document the rim cracking. In addition, the rest of the rotor was fully nondestructively tested and

mechanically inspected to assure there were no other problems or defects that would require further repair or render the rotor unserviceable. No other defects were found. The disk rim was then parted off the first rotor. Half the disk rim was chemically analyzed and mechanical property tested, while the other half was used for a weld test mock-up. Chemical analysis showed the base material was a NiCrMoV low alloy steel with the composition shown in Table 5. It should also be noted that the relatively high levels of phosphorous, sulfur and other tramp low melting elements could both affect weldability, toughness, and the potential for temper embrittlement. Although these are high by today's standards, they are typical of what could be expected for a 30 year old rotor that was made with less sophisticated melting practices.

Table 5. Chemical Composition.

Nickel	1.93%
Chromium	1.46%
Manganese	0.55%
Silicon	0.20%
Molybdenum	0.48%
Vanadium	0.093%
Carbon	0.27%
Sulfur	0.031%
Phosphorous	0.025%
Aluminum	<0.01%
Copper	0.09%
Tin	0.008%
Antimony	0.008%
Arsenic	0.02%

The mechanical properties of this disk are shown in Table 6. Review of the base metal mechanical properties showed tensile strengths and hardnesses were typical for this vintage and type turbine. However, the impact properties were significantly lower than expected, causing concern about the materials toughness. This was also shown by the higher than expected fracture appearance transition temperature. To evaluate the effects of heat treatment on the material toughness and strength, a tempering study was done at both 1200°F and 1300°F (649°C and 704°C). Test results after the 1200°F (649°C) heat treatment revealed the properties shown in Table 7. Test results after the 1300°F (704°C) heat treatment showed that the tensile strength had been significantly reduced. Therefore, this heat treatment was given no further consideration.

Table 6. Mechanical Properties.

Tensile Strength (Ksi)	107.7*
0.02% Yield Strength (Ksi)	83.3*
Elongation (%)	16.5*
Red. of Area (%)	26.2*
Brinell Hardness	224**
Impact Test (ft-lb @ (70°F)	5(0% Shear)***
Impact Test (ft-lb @ 250°F)	16(20% Shear)***
FATT (°F)	310°F
* Average of 5 Tests	
** Average of 12 Readings	
*** Average of 2 Tests	

Table 7. Base Metal Mechanical Properties after Heat Treatment.

	1200 °F - 8 Hrs.
Tensile Strength (Ksi)	107.0
0.02% Yield Strength (Ksi)	83.0
Elongation (%)	18.0%
Red. of Area (%)	32.5%
Impact Test (ft-lb @ 70°F)	16 (10% Shear)
Impact Test (ft-lb @ 250°F)	51 (20% Shear)

A comparison was made of the as-received and 1200°F (649°C) temper heat-treated mechanical properties, where a substantial improvement in toughness was realized. This improvement occurred without any loss in tensile strength. Since the 1300°F (704°C) tempering treatment affected the tensile strength, the original rotor tempering temperature was probably between 1200°F and 1250°F (649°C and 677°C). The recovery of the toughness values after the 1200°F (649°C) tempering treatment indicated that some degree of temper embrittlement had occurred during service. Consequently, the 1200°F (649°C) postweld heat treatment was recommended for the weld repair. A preweld heat treatment was also recommended for the entire rotor but due to customer preference was not done.

The tested base metal properties and chemistry were a very good match to the proprietary and proven low alloy steel filler material. Figures 15 and 16 show the comparison of the weld metal (curve) and the base metal data (triangle data point). From the data, it can be seen that the mechanical properties of the weld, met or exceeded the properties of the base metal with the impact properties/toughness being significantly better when comparing both impact energy and FATT.

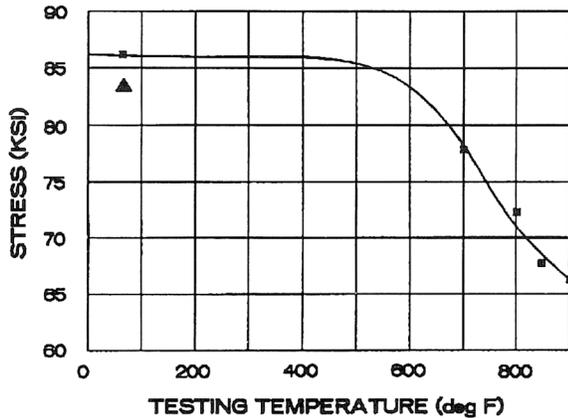


Figure 15. Comparison of Weld Metal Yield Strength to Tested Base Metal Data (Triangle).

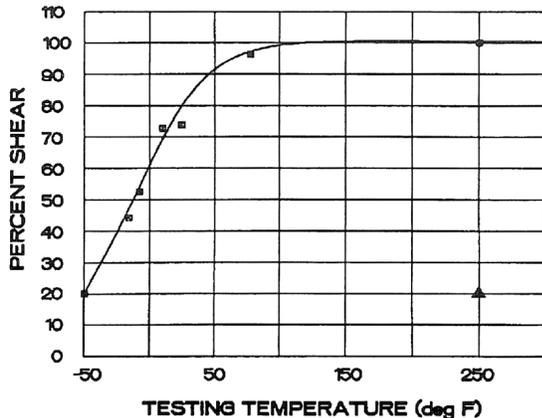


Figure 16. Comparison of Shear Percent of Weld Metal to Tested Base Metal Data (Triangle).

A weld mock-up was done to simulate the actual welding on this rotor. An approximate 30 degree arc of the parted-off disk was attached into a plate that was machined to the same diameter as the fifth stage disk to be repaired. A three-inch radial build-up was deposited on the mock-up using the mechanized submerged arc process and the standardized procedure with one exception. The only modification to the procedure was that the first three layers of the weld deposit were applied using smaller diameter wire and lower heat input to minimize the potential for hot cracking due to the higher than normal impurity levels in the disk. The mock-up deposit applied using a modified process did not exhibit any defects after inspection using UT, MT, and metallographic techniques.

Stress Analysis and Design Review

In order to confirm the stress analysis results of the customer's consultant and to review the stress levels against the authors' company internal design criteria, a steady-state, axisymmetric, 2-D finite element analysis was completed for both the blade root and disk rim. The model was generated from dimensions acquired through reverse engineering using a five-axis coordinate measuring machine and manual measurements. The engineering FE model of the blade root and disk rim is shown in Figure 17.

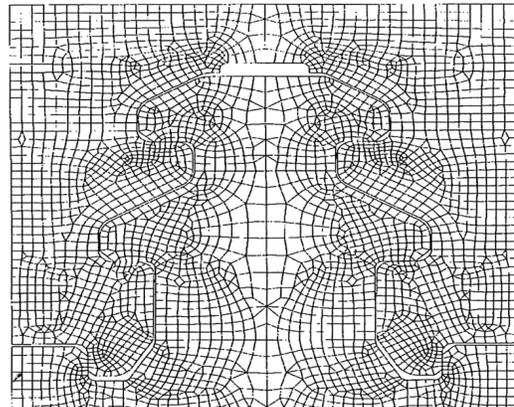


Figure 17. FEA Model of Blade Root and Disk Rim.

The configuration of the disk rim was a tangential entry male fir tree and the blade root was a female fir tree type. The calculated stresses are shown in Figures 18 and 19 for the blade root and disk, respectively, and were all within the authors' company design criteria when considering both centrifugal and steam bending stresses. Goodman factors also exceeded the criteria for fatigue margin. It should also be noted that the high stress location of the blade root corresponded with the failure location. However, the crack locations on the disk were not at the maximum stress location in the pressure land fillet radii, but rather at the end of the pressure land where fretting was noted. This evidence suggests a fretting fatigue mechanism caused by blade vibration and high contact stresses were the reasons for the disk cracking (Figure 20).

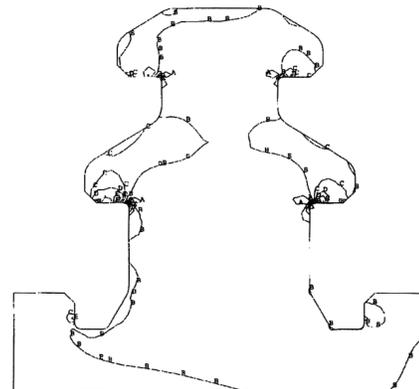


Figure 18. FEA Iso-Stress Profiles of Disk Rim.

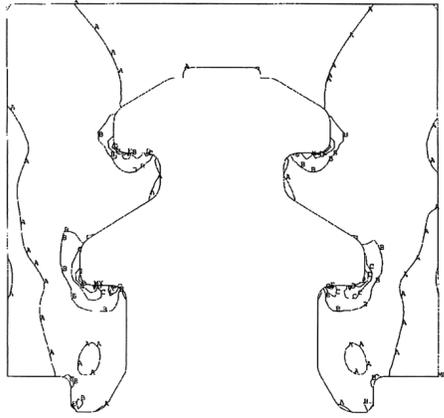


Figure 19. FEA Iso-Stress Profiles of Blade Root.

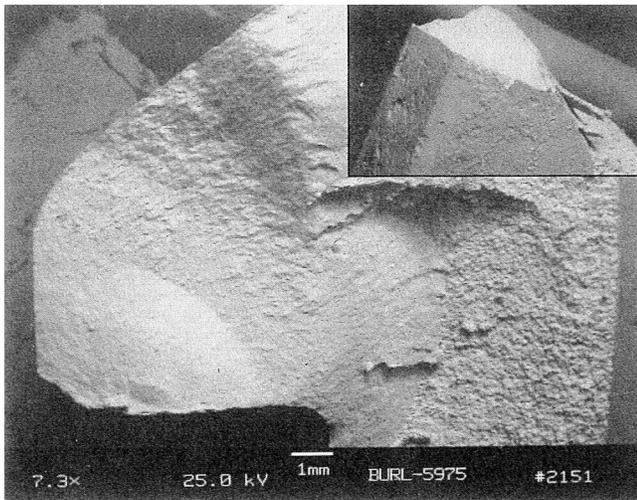


Figure 20. SEM Fractograph Showing Fatigue Fracture (Top) and Heavy Fretting (Top Corner Insert).

## CONCLUSION

The disk cracking was caused by fretting fatigue induced by blade vibration. Mechanical modifications to the upstream diaphragm and blade design (tighter dimensional tolerances), material (422 SS) and processing (shot-peening) changes were adopted to solve the blade and thus the disk cracking problems. Restoration of the fifth stage disks of both units was successful using the mechanized submerged arc welding process and specialized procedures adapted for this application. It should be noted that similar testing and analysis were also completed for the second rotor. However, it was not reported in order to minimize the length of this case study and because these data gathered for the second rotor were similar to the first rotor. In addition, the repair was accomplished in an identical manner. The restored rotors were installed in 1993 and have been operating normally ever since.

### Turbine Blades

The most common type of failure in turbine blades is fatigue and generally most OEM's replace the blades with new. Another failure in blades is in the latter stages due to liquid droplet erosion.

### Liquid Droplet Erosion

The damage of rotor blades in the latter low pressure stages of steam turbines by condensed water droplets can be a problem that has troubled designers and operators for many years. The damage consists of removal of material from the leading edge and adjacent convex surfaces of the moving blade. It is related to the wetness conditions in the low pressure regions and the velocity

with which the surface of the blade strikes the water droplets. Stresses produced by impact of drops have been calculated by existing theories to be sufficiently high to initiate damage in latter stages of blades in a steam turbine. Turbine experience and laboratory testing have shown that erosion rate is time dependent with three successive zones: a primary zone in which damage is initiated at slip planes with little or no weight loss, a secondary zone where the rate rises to a maximum, and finally a tertiary zone where the rate diminishes to a steady-state value. Moreover, it is this tertiary region that is important to designer and operator alike rather than the initial and secondary zones since it is this region that the turbine erosion shields operate for most of their lives (Figures 21 and 22).

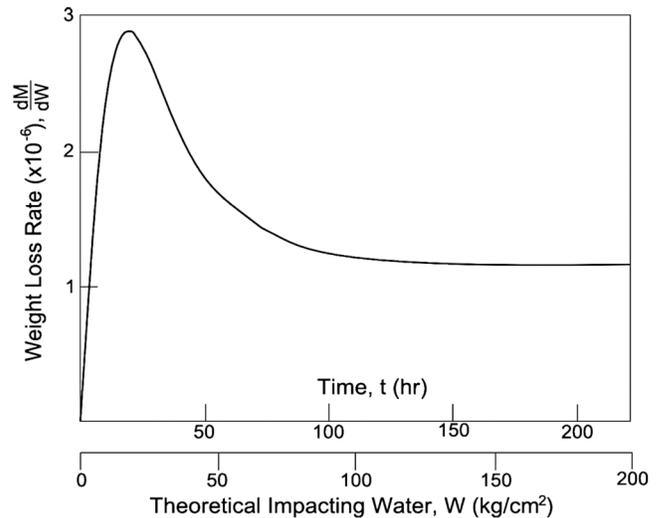


Figure 21. Erosion Rate of 630 DPH, 18W-6Cr-0.7C Tool Steel Comparator Specimens.

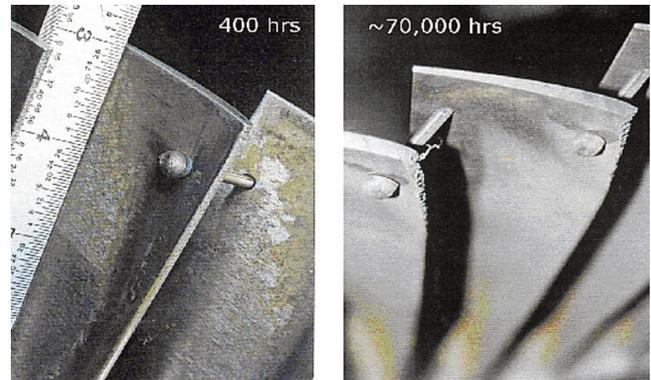


Figure 22. Images Showing Erosion of Blades from the Same Turbine after 400h and 70,000h.

While not strictly coatings, various countermeasures have been utilized by OEM's, including water drainage devices in cylinder wall, flame or induction hardening of the leading edge of the blade, and applying Stellite® or tool steel strips to the leading edge of blade by welding or brazing. All of the above methods show some degree of success, with the Stellite® material providing the better performance in the more stringent water droplet environment (Dowson, et al., 2008).

## SUMMARY

A review of repairs has been presented for centrifugal compressors and steam turbines. Special attention has been given to address some of the various types of repairs and steps taken to prevent or minimize reoccurrence.

REFERENCES

- Barsom, J. M. and Rolfe, S. T., 1977, *Fracture and Fatigue Control in Structures*, Englewood Cliffs, New Jersey: Prentice Hall, Second Edition, p. 284.
- Dowson, P., Bauer, D., and Laney, S., 2008, "Selection of Materials and Material Related Processes for Centrifugal Compressors and Steam Turbines in the Oil and Petrochemical Industry," *Proceedings of the Thirty-Seventh Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University College Station, Texas pp. 189 to 209.
- Dowson, P., Wang, W., and Alija, A., 2005, "Remaining Life Assessment of Steam Turbine and Hot Gas Expander Components," *Proceedings of the Thirty-Fourth Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 77-92.
- Gandy, D. and Smith, R., August 2001, Transaction Sm. Rt 16, Washington D.C.
- Glinka, G. and Lambert, S., 1993, "Modeling of Fatigue Crack Growth in Flat Plate Weldments and Tubular Welded Joints," *Fatigue Design*, London, England, pp. 73-93.
- LaFave, R. A., 1991, "Submerged Arc Weld Restoration of Steam Turbine Rotors Using Specialized Welding Techniques," *Proceedings of the Twentieth Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 19-34.
- LaFave, R. A. and Wiegand, R., April 1994, "Economic Repair of Turbomachinery Shafts by SAW," *Welding Journal*, pp. 39-44.
- Niu, X. and Glinka, G., 1989, "Stress Intensity Factors for Semi-Elliptical Surface Cracks in Welded Joints," *Int. J. Fracture*, 40, pp. 255-27.
- Pisarski, H. G. and Davey, T. C., "Fracture Toughness of Steel Plate to AISI 4140," The Welding Institute Private Report.
- Shen, G. and Glinka, G., 1991, "Weight Functions for a Surface Semi-Elliptical Crack in a Finite Thickness Plate," *Theoretical and Applied Fracture Mechanics*, 15, pp. 247-255.
- United Technologies Research Center, November 4, 1980, Private Report.

BIBLIOGRAPHY

- Dowson, P., 1995, "Fracture Mechanics Methodology Applied to Rotating Components of Steam Turbine and Centrifugal Compressor Rotors," 3rd International Charles Parson's Conference, Tyne, United Kingdom.
- Niu, X. and Glinka, G., 1987, "The Weld Profile Effect on Stress Intensity Factors in Weldment," *Int. J. Fracture*, 35, pp. 3-20.

ACKNOWLEDGEMENT

The authors are grateful for the support from the Materials Engineering Department and Global Technical Services and recognize the Elliott Group for permission to publish the paper.

