

# IMPELLER REPAIR TECHNIQUES FOR CENTRIFUGAL COMPRESSORS

by

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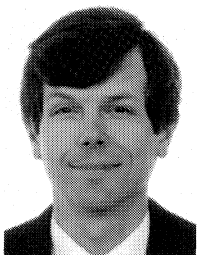


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## ABSTRACT

Successfully repairing centrifugal compressor impellers requires careful consideration and planning. The selection of techniques for inspection, material, and welding procedures are determined by numerous factors. Original design and manufacturing techniques, the nature of a failure, and environmental or process concerns all play a role.

The relevant issues are addressed that may assist the user's maintenance personnel in formulating an overall strategy to extend the service life of their impellers through the selection of adequate repair procedures.

## INTRODUCTION

Compressor performance and reliability are closely related to the condition of the impellers. Impeller stresses are higher and the construction is more complex than for any other component on the rotating element.

To ensure continued troublefree operation of the unit, the rotating element should be inspected on a regular basis. The approach must be systematic and well documented. Current testing and inspection results should be compared with data from earlier inspections, to evaluate any observed deterioration, and its impact on the impeller's life expectancy. The repair engineer must be knowledgeable in impeller design, environmental conditions, material compatibility, and failure characteristics. The repair strategy must look beyond simply fixing cracks. Lessons learned from the failure analysis should be incorporated to minimize future problems and unexpected failures.

## COMPRESSOR PERFORMANCE

To understand how and when to apply various impeller repair techniques, it is first appropriate to understand the basis for the original design of the equipment.

Centrifugal compressors transform mechanical shaft energy into pressure by imparting kinetic energy (velocity) to the gas through a continuous rotating motion.

This is accomplished through a combination of one or more rotating impellers and fixed directing parts with vanes in which the gas is first speeded up and then its velocity head is converted into pressure.

The fixed parts are at the discharge of the impeller and include the diffuser and a volute or scroll that converts the velocity head into pressure.

Depending on the required pressure rise or head, turbomachines can have one impeller (single stage), or they can have several impellers operating in series with alternating fixed vanes.

The compression work done by a centrifugal compressor stage is most frequently represented as the energy absorbed by a unit mass of the gas, as it moves from the inlet to the discharge of a compressor. It is most frequently expressed as head (in feet). The thermodynamic expression for polytropic head ( $H_p$ ) is expressed as:

$$H_p = z RT_1 \left( \frac{n}{n-1} \right) \left( \frac{P_2^{\frac{n-1}{n}}}{P_1} - 1 \right)$$

The geometric expression of polytropic head as it relates to the velocity triangle at the OD of the impeller is:

$$\frac{1}{g} u_2^2 \eta_p \frac{V_{u_2}}{u_2} \frac{V_{u_2}}{V_{u_2}}$$

This relationship between the thermodynamic head (that can be calculated from the gas conditions) and the geometric head, which can be determined from the performance of geometrically similar impellers, is the cornerstone of performance estimation of centrifugal compressors.

**IMPELLER DESIGNS**

Impellers have blades or vanes that may have exit angles at the OD that curve backward, radially or forward (Figure 1). Each type has a characteristic shape to its head/capacity curve.

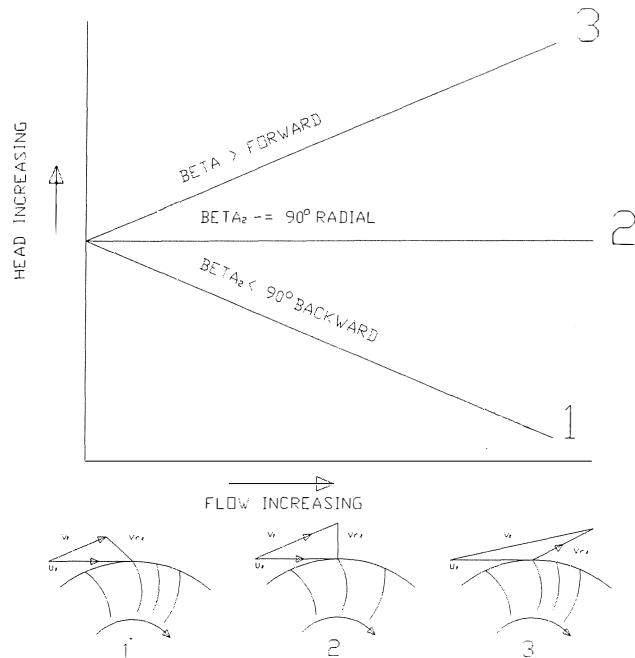


Figure 1. Blade Design Chart.

Each type has advantages. Most industrial compressors use radial blades (higher head, slightly lower ( $\eta_p$ ) due to lower reaction) or backsloped blades (lower head higher ( $\eta_p$ ) due to higher reaction).

Impeller construction can be classified as follows:

- Fully Enclosed (with cover disk)
- Open Front (no cover disk)
- Semi-Open Front (with shrouding or band)
- Open Front and Back
- Double (Back to Back) for thrust equalization (Figure 2)

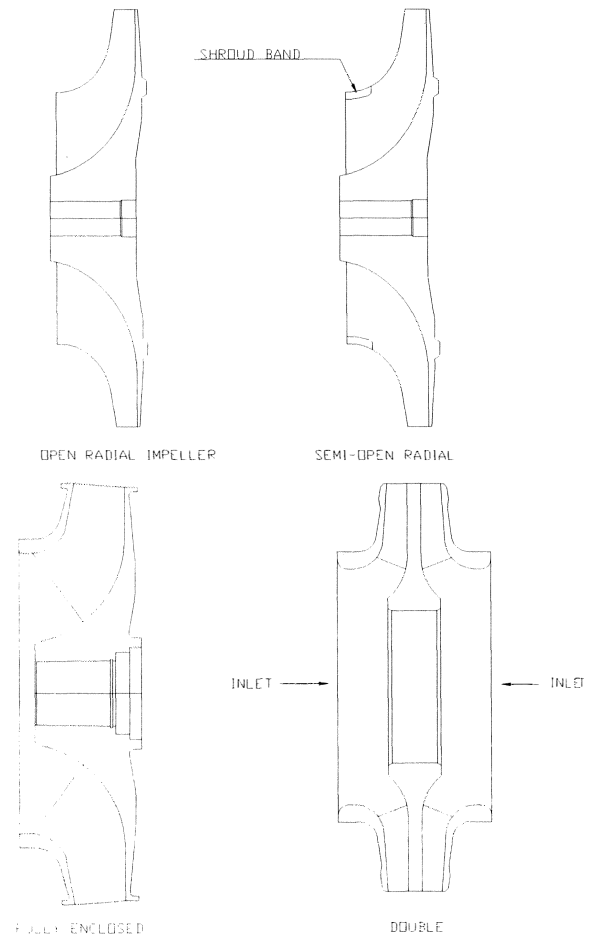


Figure 2. Impeller Identification Chart.

Semiopen impellers use a small shroud ring at the OD of the impeller eye to tie together the blades and reduce vibratory stresses. This can cause some problems.

- The ring is highly stressed, and subject to growth due to centrifugal force, thus the points of attachment between the ring and the blades results in a stress concentration, which may result in a reduction in the maximum allowable tip speed on a comparable open impeller.

- The ring is an interruption to the flow path, which may disrupt the flow into the impeller, resulting in excitation of the blades or reduction in efficiency.

The ring is also a site for fouling deposits to collect. Reduced vibratory stresses can now be achieved in open impellers by detuning blade natural frequencies.

Fully enclosed impellers (with a cover disk) are used in single stage compressors with high thermal or mechanical distortions or in multistage compressors where high efficiency is required. With multiple open face impellers on a common shaft, it would be impossible to control the clearance between the impeller blades and the casing due to the thermal expansions of the rotor and the casings. With the cover welded to the blades, there is no clearance to control, and premium efficiency is obtained.

**FABRICATION TECHNIQUE**

Impeller fabrication techniques can be classified as follows:

- Machined from a solid forging—The advantages include the absence of welding stress, very smooth surface finishes, extremely small blade fillets, consistent blade geometry, and higher tip speeds.
- Electron Discharge Machining (EDM)—used to manufacture closed impellers.
- Multiaxis milling—used to manufacture open impellers. Five axis mills are required for 3D blade profiles.
- Investment Castings—The advantages include the absence of welding stresses, smooth surface finishes, extremely small blade fillets (Figure 3), minimal finish machining, and low replacement costs. The disadvantages include high initial pattern costs, the inability to accommodate smaller discharge vane spacing and thinner blades, and the inconsistency of quality between different foundries.

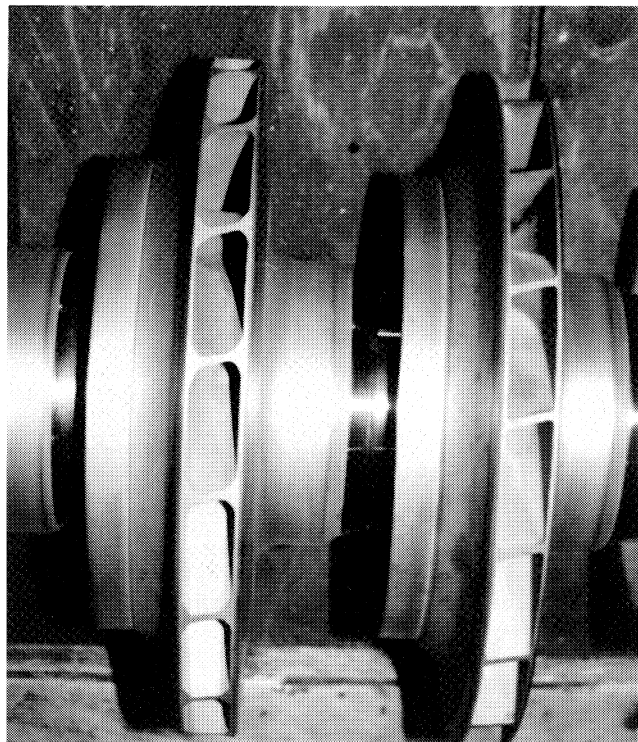


Figure 3. The Impeller on the Left is the Finished Product for the Revamped Unit in Figure 16. Note the difference in the weld fillet on the revamped wheel and the much smaller fillet on the cast impeller at the right.

- Fillet Welding—Advantages include material strengths that can be superior to the base metal, high tip speeds, well developed

procedures and commonly available equipment to ensure weld quality, moderate pricing. The disadvantages include the extensive grinding time required to upgrade welds, grossly oversized fillets on small impellers, and the inability to produce impellers with discharge vane widths below 0.300 in or blade thicknesses below 0.125 in.

*Electron Beam Welding*—not sufficiently developed at this point to be universally applicable. Problems include inadequate weld fillets and gap due to inadequate penetration. Adequate inspection is difficult.

*Slot Welding*—Advantages include speed of manufacture, moderate pricing, reduced grinding time. Disadvantages include inconsistent burn through producing gaps and inconsistent weld fillets. Cover distortion can be significant and the cover weld is difficult to repair.

*Brazing the Cover*—The advantages include reduced stress levels, good mechanical properties of the brazed joint to 90 percent to 100 percent of the base metal, minimal distortion, moderate pricing, no bottom limit on discharge vane width or blade thickness. The disadvantages include inability to repair the cover and the use of a sophisticated UT process to ensure bonding of the cover. This limits users in performing their own inspections (Table 1).

Table 1. Impeller Manufacturing Limits.

Type	Fabrication Technique	Tip Speed Limit
Open	Machined from solid	1450
Closed	EDM	1200
Closed	Investment cast	1150
Closed	Blades machined from solid/welded cover	1200
Closed	Blades machined from solid or welded to hub/brazed cover	1000
Closed	Riveted	850

**INTRODUCTION TO IMPELLER STRESS ANALYSIS**

As mentioned previously, impeller stresses can be categorized by origin, type, and location of interest within the various types of impellers described above.

The three types of stresses are steady state, thermally induced, and vibratory stresses.

Steady state stresses are centrifugally induced due to rotation of the impeller and are proportional to the square of the tip speed of the impeller (Figure 4).

The impeller is also subjected to steady stresses as a result of the mean gas forces present in service, although these are small (five percent to ten percent of the centrifugally induced stresses).

Other forms of steady state stresses are those that result from the initial shrink fit used to mount the impeller on the shaft. Typical shrink fits are 0.001 to 0.002 in/in of diameter. This level of shrink is necessary to maintain positive mounting of the impeller including torque transmission capability and the loss of shrink fit due to rotational speed or differential thermal expansion between the impeller and the shaft. Excessive interference results in abnormally high stresses at the impeller bore, which is already the most highly stressed area on a single stage impeller due to rotating stresses.

The second category of impeller stresses are thermally induced stresses that result from exposure of the impeller to varying temperatures either in manufacture or operation.

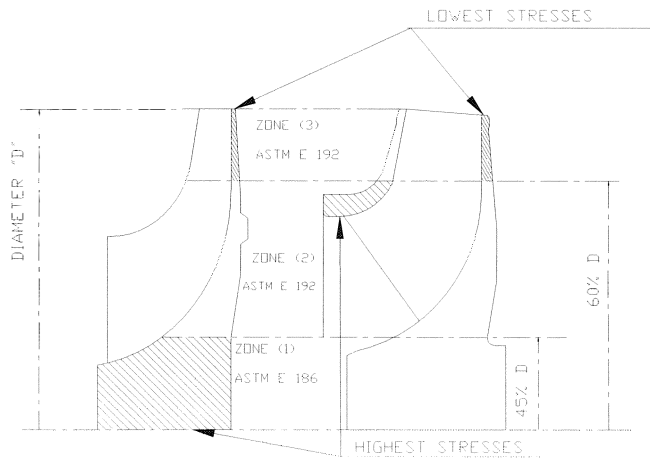


Figure 4. Inspection Chart for Open and Closed Impellers Identifying Stress Intensity.

Operation in surge or recycle for an extended period of time produces elevated operating temperatures, which can result in the loss of shrink with attendant spinning of the impeller on the shaft. Any signs of high heat (rubs or bluing) detected during a turnaround should be cause for detailed inspection of the impellers for cracks, or degradation of the impeller bore (Figure 5).



Figure 5. This Multistage Wheel Rubbed on the Upstream Diaphragm. A three in section up to one in deep was machined off the cover at the eye. The repair will include insert of a new forged cover section at the eye.

Perhaps the most sophisticated area of impeller stress analysis is the area of vibratory stresses. These stresses are most frequently associated with open impellers when the first natural

frequency of the unrestrained blades coincides with a multiple of the operating speed (Figure 6). The blades vibrate in response to the once per revolution gas disturbance created when a blade passes the tongue area of the discharge scroll (Figure 7).

These gas forces are the primary excitation for vibratory stresses. The excitation forces are generally proportional to gas pressure, the molecular weight, the pressure ratio, and operating point on the performance curve (rated vs surge or choke). These forces and natural frequencies were not well known or understood until the late 1970s and early 1980s when detailed 3D finite element analysis of the impeller and its blades was undertaken. An extensive program of finite element analysis, static

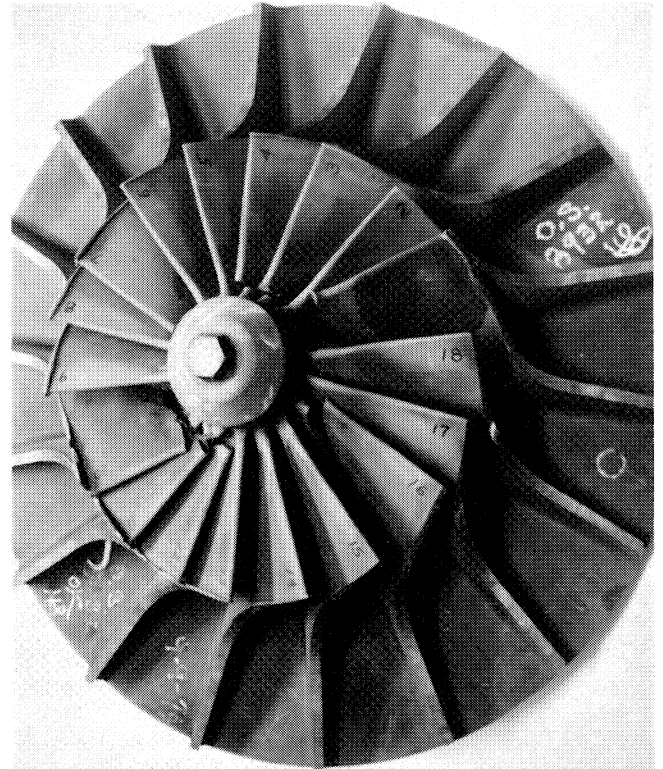


Figure 6. A Welded 4140/4130 36 in Diameter Single Stage Impeller. The damage is due to a premature fatigue failure accelerated by high vibratory stresses related to resonant blade frequencies. The rubbing occurs after the first blade failures. Blade 16 is an obvious fatigue fracture. Blade 10 failed after rubbing and shows more signs of mechanical tearing.

model testing of impellers (including disk and blade frequencies,) and rotating vibration tests with strain gauged impellers were used to develop the design and analytical techniques.

As a result, the practice has been to detune the impeller blade natural frequencies from multiples of running speed (for fixed speed machines). Blade frequencies as high as eight times the running speed have resulted in blade failure. The detuning is accomplished via the use of finite element preprocessor programs that enable straight forward calculation of blade natural frequencies that are detuned from resonance in the design stage. All open impellers have their blades ring tested on the shop floor to ensure there is no possibility of resonance in the field (Figure 8).

For variable speed units, more conservative design limits on top speed, impeller design, and calculated vibratory stresses of

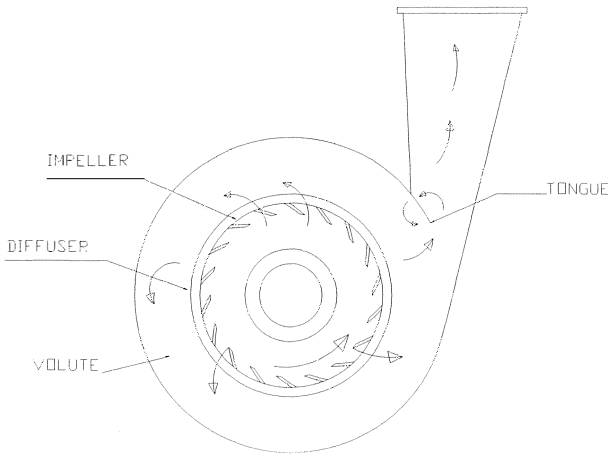


Figure 7. The Single Stage Discharge Scroll Tongue Can Cause a Gas Force Disturbance.

1.0 BLADE RINGING PROCEDURE:

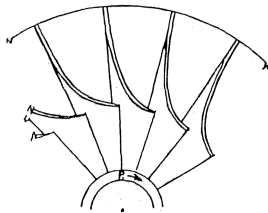
1.1 USING THE STAMPED "P" OF THE P NUMBER AS THE No.1 BLADE, RING EACH BLADE AND RECORD THE FIRST NATURAL FREQUENCY OF EACH IN THE SPACES PROVIDED BELOW. BLADE ORDER IS GIVEN BY THE DIRECTION OF THE ARROW WITH THE IMPELLER REMAINING STATIONARY AS SHOWN IN THE SKETCH.

JOB No. \_\_\_\_\_  
 "P" No. \_\_\_\_\_

CHECK ONE:  
 A  IMPELLER AFTER MACHINING  
 B  IMPELLER AFTER BALANCE  
 C  ROTATING ELEMENT

UNDESIRABLE FREQUENCIES  
 Hz TO \_\_\_\_\_ Hz  
 Hz TO \_\_\_\_\_ Hz  
 Hz TO \_\_\_\_\_ Hz

RECORD ONLY



BLADE No.	FREQ. (Hz)	BLADE No.	FREQ. (Hz)
1	_____	11	_____
2	_____	12	_____
3	_____	13	_____
4	_____	14	_____
5	_____	15	_____
6	_____	16	_____
7	_____	17	_____
8	_____	18	_____
9	_____	19	_____
10	_____	20	_____

OPERATOR CLOCK No. \_\_\_\_\_ DATE \_\_\_\_\_  
 INSPECTOR \_\_\_\_\_ DATE \_\_\_\_\_

ORIGINAL TO DATA PAK  
 BLUE COPY TO ENGINEERING  
 HARD COPY TO SHOP ROUTING

Figure 8. A Blade Frequency Data Sheet Used for Ring Testing Open Face Impellers Before and After Repairs. The blades are ground to produce acceptable frequencies as required.

resonance have been developed to ensure satisfactory life under the most adverse conditions.

The outlined repair techniques are intended to restore a well designed, correctly applied impeller to its original condition and performance level. Repair alone is clearly inadequate if the impeller has experienced a catastrophic failure such as: loss of a blade (fatigue failure) in an open impeller; permanent distortion (growth) following overspeed test; or a rerate that will result in operation beyond the original overspeed test speed.

For these cases, the impeller should be analyzed using current 3D finite element stress analysis techniques to determine max-

imum steady state stresses in the hub and cover, along with the best techniques for detuning the blades from the apparent blade frequencies.

A typical 3D finite element analysis model for vibratory stress calculation is shown in Figure 9. A plot is shown in Figure 10 of the harmonics of blade frequencies vs operating speed for use while detuning.

OPERATION FAILURES

All impeller failures have at least one thing in common. Stress is involved. This may be residual stresses related to welding or machining operations, rotational stresses, thermal stresses,

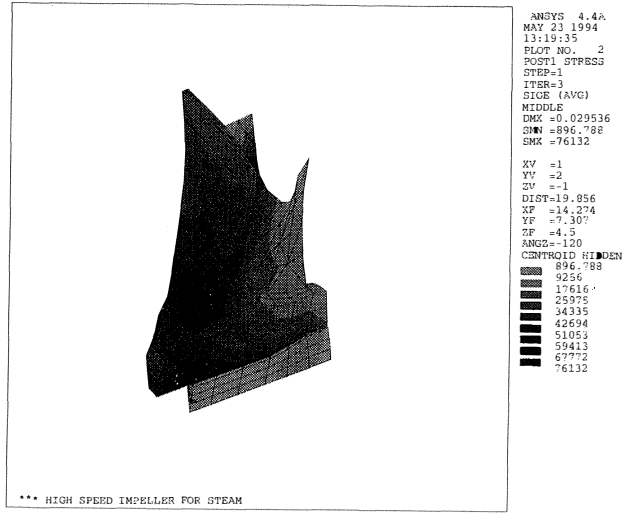


Figure 9. Finite Element Stress Analysis for an Open Face Impeller.

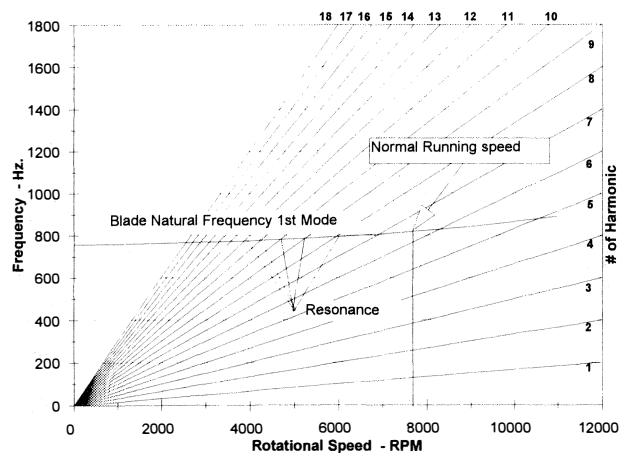


Figure 10. Rotating Speed Vs Harmonic Frequency.

clamping stresses, vibratory stresses, or a combination of all of them.

The detrimental effect of these stresses is the creation of the force required to initiate and propagate cracks in the impeller. Visual inspection, nondestructive testing, and destructive testing processes are used to identify the mode of failure.

Common terminology for the classification of cracks in metals is "ductile" and "brittle" fractures. Ductile fractures are

characterized by gross plastic deformation and jagged surface texture. Brittle fractures do not exhibit large scale plastic flow and have a rubbed or ground surface appearance (Figure 11).

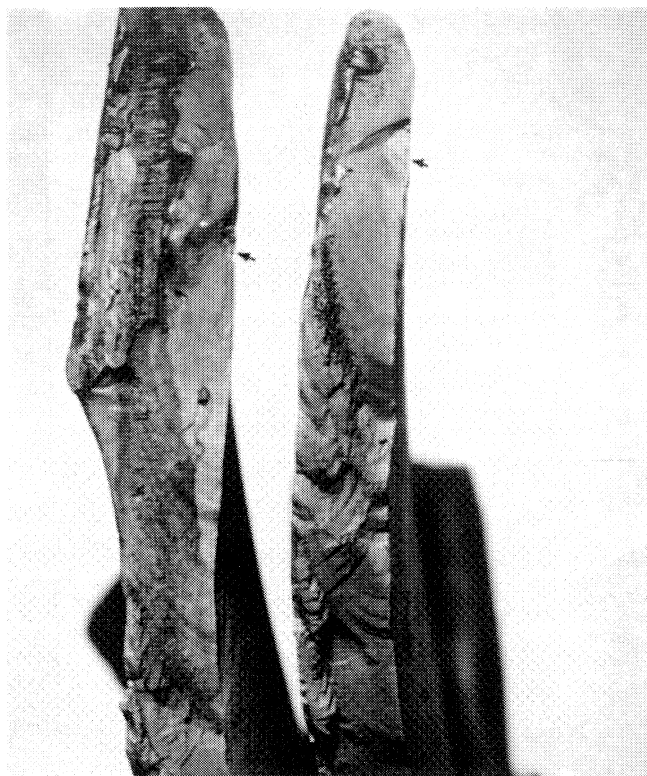


Figure 11. Two Failed Single Stage Blades Showing the Fracture Initiation Sites, Beach Marks, and the Eventual Tearing Action.

A “fatigue fracture” occurs due to combined steady state and cyclical stresses. The combined stresses are much lower than the stress required for a static rupture. Normally, the initiation of the fatigue crack is local to stress concentrations at a discontinuity such as fillets, slag inclusions, oversized or jagged pitting, or even granular irregularities. The peak stress at these discontinuities is higher than the average stress of the surrounding areas, therefore, they are referred to as “stress raisers.”

Once a site develops, the continued cyclical stresses propagate the crack with the stresses concentrating at the tip of the crack. The rate of development of the crack is related to the amplitude of the cyclical stresses. Unbalance of the rotor, misalignment, and especially blade resonance in open impellers, can cause and accelerate crack growth.

If the crack is not detected and repaired, it can spread until the cross section is reduced and a final tensile failure occurs. The failed section will exhibit areas of both “brittle” and “ductile” fracture. In most cases, the brittle region will be characterized by relatively smooth concentric “oyster shell” or “beach” marks radiating from the original crack site. The final area of rupture will have a jagged surface with significant deformation typical of a ductile fracture or tearing.

Compression processes can produce conditions that promote or accelerate the deterioration of impellers. Erosion and corrosion are common problems related to adverse process conditions.

Liquid carryover in compressor processes leads to liquid impingement erosion. Material loss occurs due to the high speed

collision of liquid droplets with the impeller surface. The initial rate of erosion is dependent upon the relative velocity of the impeller and the fluid component. The impact of individual droplets on the impeller produce miniature craters and circumferential cracks in the surface. Subsequent impacts and the corresponding high velocity radial flow of liquid out of the craters result in the continued growth of pits and fissures.

In an advanced state of development the eroded surface has a honeycomb appearance (Figure 12). This roughened surface and the work hardening effect of the constant impacting eventually leads to a reduction in the rate of erosion.

Additional erosion occurs due to the acceleration of liquid through the impeller. The characteristic cutting that is produced is most prominent on the working side of the discharge vane at the weld fillet (Figure 13).



Figure 12. The Eye of a Single Stage Impeller Exhibits the Honeycomb Appearance Characteristic of Corrosion Damage.

The cutting, jagged pits, and the roughened surface are ideal “stress raisers” that can produce the initiation site of fatigue failure (Figure 14).

Corrosion occurs due to the electrochemical reaction of the gas corrodents with the impeller materials. This electrolytic attack occurs at a microstructure level.

Uniform corrosion occurs when the exposed material has a homogenous chemical composition and microstructure. Uniform corrosion at steel impellers produces a roughened surface due to a loss of material. The life expectancy of an impeller can be estimated by comparing the rate of material thinning with that of previous inspections. This rate is subject to change due to environmental or process variations. As an expedient means of preventing a serious failure once a problem has been identified, frequent inspection intervals should be scheduled to prevent an unexpected failure related to an acceleration in the rate of attack (Figure 15).

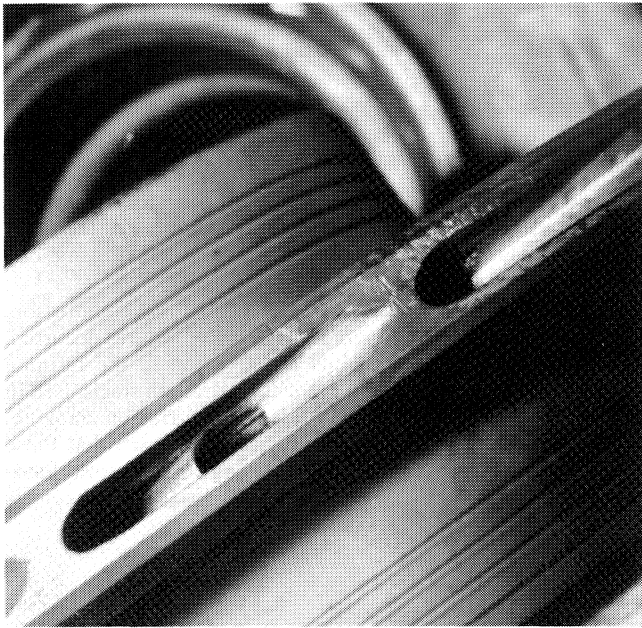


Figure 13. A Closed Impeller with Erosion Damage. Note the cutting at the edge of the discharge vane and the hole in the center of the blade due to the general thinning by high velocity liquid.

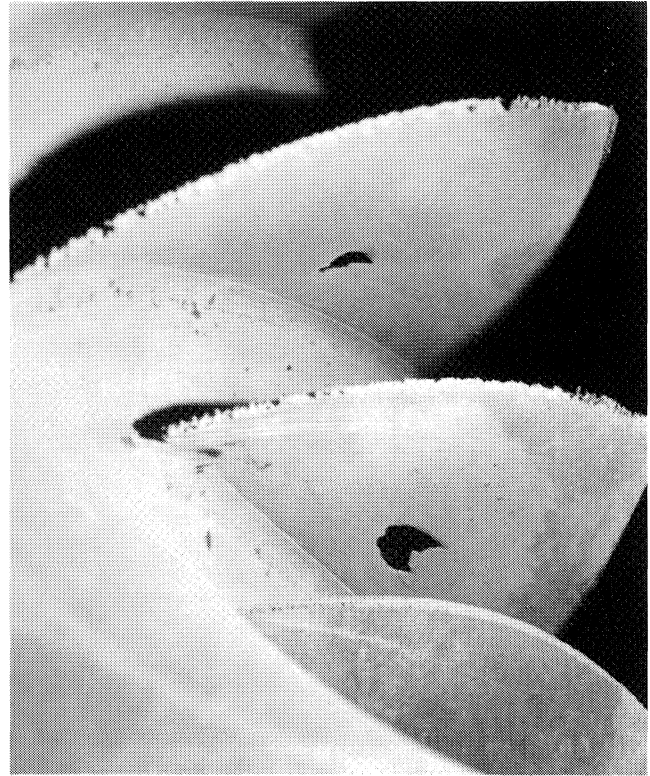


Figure 15. A Closed Impeller That Suffered Extensive Corrosive Damage. Note the large aspirations and pitting at the eye. The surface of the blade experienced significant metal loss and an eventual hole due to uniform corrosion.

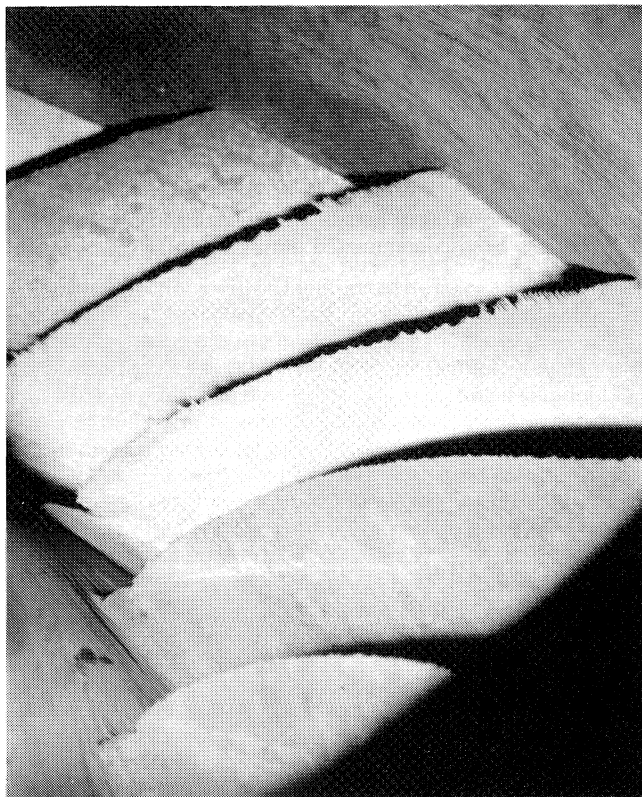


Figure 14. A Closed Impeller That Experienced Severe Erosion Damage. Note the sharp knife like cutting at the eye and the reduction of area at the weld on the base of the blade and hub. The erosion is also obvious on the surface of the hub.

Pitting corrosion occurs due to an inhomogeneity on the surface, a localized loss of passivity, or the breakdown of protective oxide coatings. Widely dispersed pits tend to penetrate into the metal more rapidly and the surrounding surfaces tend to be less affected by general corrosion.

Erosion and corrosion have detrimental effects on the fatigue life on an impeller. The general roughening of the surface introduces stress raisers, and deep pitting and general material loss reduce the overall cross section resulting in increased stress amplitudes. This material loss can also change the natural frequency of a previously detuned blade and drive it into a harmful range. Material loss at the discharge can alter the exit angle and reduce the designed head (Figure 16).

Additionally, corrosion can greatly accelerate the growth of an existing crack. Once a crack has been initiated, the corrosive agent attacks the walls and base of the crack. Dislodged material from this reaction forms a wedge at the tip of the crack, increasing the peak stress during each cycle. This behavior is referred to as "corrosion fatigue." The fracture is brittle and very similar in appearance to a standard fatigue fracture except that the surface normally exhibits a discoloration related to the corrosive agent.

Although erosion and corrosion have been discussed separately, it should be noted that in many compression processes, both conditions exist simultaneously. In some cases, they act in concert to cause a highly accelerated phenomenon known as "erosion-corrosion." Impingement corrosion is a severe form of erosion-corrosion affecting impellers. Liquid impingement destroys protective oxide surface films and exposes new reactive surfaces to the uneroded areas. The resulting electrolytic action between the surfaces leads to rapid localized corrosion. The area

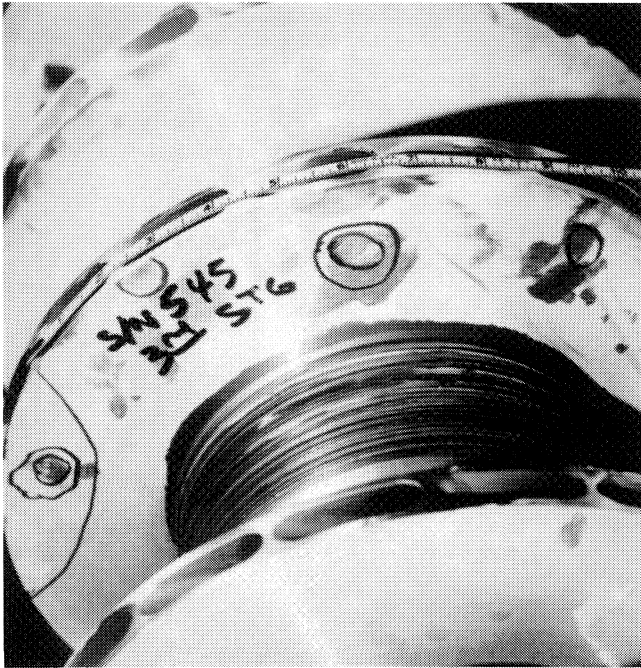


Figure 20. Indications Revealed by Dye Penetrant Inspection.

construction. The impeller is immersed in water to help the propagation of the sound wave.

Industry inspection standards are vague and indecisive and ultimately tend to come full circle to what the buyer and seller can jointly agree upon. Below are some recommended NDT/MPI guidelines.

#### NDT/MPI ACCEPTANCE AFTER-REPAIR GUIDELINES

- Linear indications—none allowed.
- Cluster porosity—depends on extent.
- Slag inclusion indications—none allowed on repaired area.
- OD tips nonfusion—none allowed.
- Isolated porosity—depends on extent.

Austenite/ferrite stringer indications (acceptable)—lightly polish indication area, LPI with fluorescent, water wash penetrant, remove LPI indications, reverify with wet MPI. White light visual inspection required to identify porosity that may not produce MPI indications.

The type of inspection required depends on the nature or the material, extent and location of repair, environment of service, history of operation and former repairs, type/method or repair enacted and current or near future operating conditions. This requires a broad understanding of all the factors in play in order to direct the inspection strategy accordingly (Table 2).

#### OVERSPEED TESTING

The operation of an impeller in a specially designed tank or pit at higher than normal operating stresses after initial fabrication or repair welding is essential to assure that the design and metallurgical processes have been adhered to and are correct. Improper material, heat treatment, stress relieving, welding, or fabrication procedures can be detected by overspeeding. The impeller is nondestructively tested (usually by MPI or dye penetrant) and then several measurements are taken and record-

Table 2. Terminology for Flaw Indication.

Discontinuity Types	Description
Linear discontinuities (hot tears and cracks)	Jagged lines of varying width. May appear as a single jagged line or exist in groups. They may or may not have definite line or continuity. They usually originate at the casting surface and generally become smaller as they go deeper. Light grinding and dye checking can verify this.
Shrinkage	Appears as a ragged area or irregular patches. Shrinkage in a subsurface discontinuity that may be brought to the surface by machining. Not usually a repair issue.
Inclusions	Isolated, irregular or elongated variations of magnetic particles occurring singly, in a linear distribution or scattered at random in feathery streaks. The indications are the result of the presence of sand, slag or oxides in the surface metal. On repairs, this type of indication is a judgement call, particularly on older impellers.
Internal chills and unfused edges.	A uniform line or band outlining the object and indicating lack of fusion between the metal object and the casting of two welded pieces. Location and extent are critical.
Porosity	Appears as rounded and elongated clusters of magnetic particles of various sizes; scattered at random. Size and location are important considerations particularly if the pores are linear and could initiate and propagate a crack.
Welds: Weld porosity, Incomplete Penetration, Undercutting, Inclusions in weld, Crater cracking.	Incomplete fusion and penetration appears as a straight continuous or intermittent linear indication. Porosity, inclusions and linear discontinuities in welds appear as described above. Welding procedure and technique need to be reviewed.
False Indications:	Prod Pattern Particles lodged in depression. Chisel marks Wrinkles Scratches
Magnetic Anomalies:	Adhering scale High external magnetic field Junction of materials of different permeability Particle build up at sharp fillet

ed on the eye, the OD and the bore. It is accelerated in a vacuum to reduce heat and required horsepower. A speed of five to 20 percent above the compressors maximum continuous speed is used. The actual percentage depends on contract requirements, whether the impeller is a repair or newly fabricated, and if the compressor is motor driven or turbine driven (generally on the higher end due to turbine trip speed). By convention, the impeller is held at overspeed speed for one minute although the stresses imparted to it from rotation are instantaneous and directly proportional to the speed squared (i.e., five percent speed increases elevate the stress 10 percent).

$$\left(\frac{N}{N_1}\right)^2 = \left(\frac{\sigma_T}{\sigma_{T1}}\right)$$

Where:  $N$  = speed

$\sigma_T$  = tangential stress

API 617 calls for testing at 15 percent above the maximum continuous operating speed for newly manufactured impellers.



Common repair practice is a 10 percent overspeed. Turbine driven units are sometimes set higher to accommodate setting up the overspeed mechanical trips in the field. Questionable impellers should never be oversped at such initial levels. Depending upon the overall condition, increase the impeller speed and inspect it in five percent increments beginning at 90 percent or less.

The amount of energy being absorbed by overspeed testing is immense and can be dangerous. A 42 in impeller, rotating at 7900 rpm has roughly the same velocity (1450 FPS) as a 0.44 magnum bullet and the overall energy is much higher (Figure 21).



Figure 21. Lowering a Single Stage Impeller into the Overspeed Tip.

Following the overspeed test, the impeller is then removed and again nondestructively tested and remeasured to detect any yielding of the material (Figure 22). Within the sensitivity of the measuring tools, no deviation is acceptable from the initial impeller diameters (Figure 23). No unexplained defect is to be left unexplored or unresolved.

Hardness is measured by comparing the effects of an indentation when applied with a known force against known samples or by electronically measuring how well a surface reflects or rebounds a known force. The more force reflected, the harder the surface. Hardness testing can ensure that a material is soft enough to run successfully in stress corrosion environments.

The materials involved can be mechanically tested if extra pieces are possible (coupons or extra blades) for strength, ductility, etc., or microscopically examined for grain structure evaluation. Nuclear activation analysis can be used to verify material composition. The piece is made radioactive by exposure to a source of radioactivity and, as each element emits different energies depending on that element and on how much is present. The examined piece's energy emission is measured and the material's composition identified. On new impellers, or on major replaced repair pieces, vendor material certifications are required.

## WELDING

Formulating a repair strategy requires the selection of a welding method and the identification of the proper equipment and material to produce the desired properties.

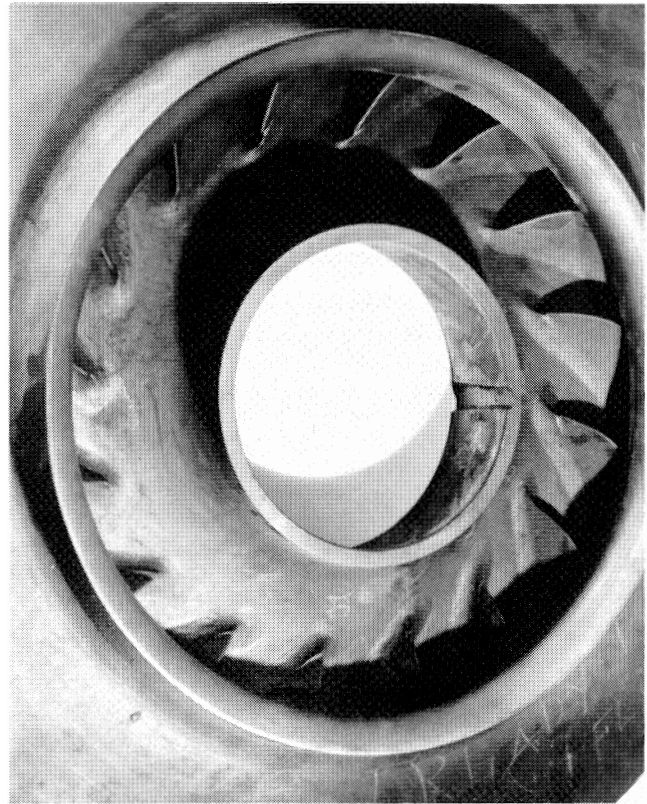


Figure 22. Blade Tearing Due to Overstressing During an Overspeed Test.

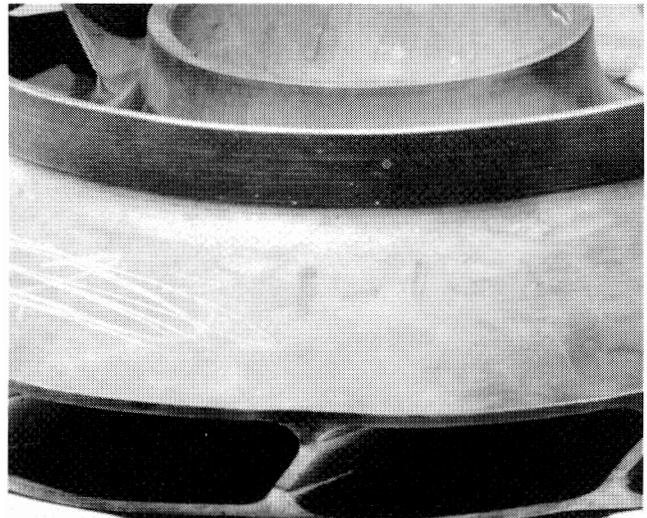


Figure 23. Cover and Back plate Distortion Occurring During an Overspeed Test. The outside diameter of this wheel grew by almost 1/2 in.

Compressor impellers have been successfully fabricated using a wide variety of the arc welding processes. The most important are shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), or (TIG), gas metal arc welding (GMAW) or (MIG), and submerged arc welding (SAW).

SMAW welding has diminished in popularity over the years due to the advent of automatic and semiautomatic processes

related to GMAW and SAW. SMAW exhibits the disadvantages of multiple arc starting sites, difficult slag removal for multiple passes, nonuniform weld finishes and lost production time due to constant rod replacement. SMAW has also been restricted to the manufacture of open impellers or smaller covered disc impellers due to the limitations of the length of coated rods, and accessibility in the channels.

The GTAW process produces a smooth concave weld requiring minimal grinding. However, it is a manual process limiting its usefulness in production welding. It is also not well suited for attaching covers.

Both GMAW and SAW can be used in semiautomatic and fully automatic applications. The SAW method has emerged as the most popular. It is fast, exhibits superior penetration, and the weld quality is smooth and consistent. A granular flux is used to protect the weld from the atmosphere. The heat generated during the weld cycle melts the flux adjacent to the weld providing air tight protection and a more controlled cooling cycle. The solidified flux is easily removed. The use of SAW and a granular flux does limit welding to a near flat weld position. To accommodate welding contoured blades and hubs in a flat position, the impeller is mounted to a weld positioner with foot peddles to allow rotating and tilting of the impeller, while the operator manipulates a semiautomatic torch.

The torches are designed in various lengths and shapes to allow access in areas outside of the line of sight. They are also equipped with spacers and supports to insure a uniform arc length (Figure 24).

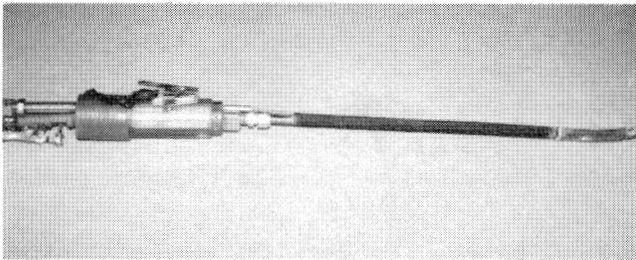


Figure 24. Semiautomatic Submerged Arc Welding Torch.

At any rate, the initial method of fabrication is not necessarily the basis of selection for the repair process. For the repair of small or isolated indications SMAW and GTAW are both popular choices. Production time is no longer a factor. For repairs to small precise locations, both methods have the advantage over SAW in that the repair weld is visible as opposed to being obstructed by the granular flux. Also, lower heat inputs become an advantage at this point.

Erosive and corrosive damage on open impellers can be severe. The outer profile of the inducer and the discharge vane normally suffer the most noticeable loss of material, but the entire blade can be subject to a reduction in thickness. Multiple passes of GTAW with a low heat input is the preferred method to restore the lost profile (Figure 25). Once a profile has been reestablished, the overall thickness can be restored by pad welding with either SMAW or SAW (Figure 26). This is followed by remachining the blade profile and the laborious task of hand grinding the weld to produce a smooth aerodynamic surface free of stress raisers (Figure 27). Welds should be ground to a 64 to 100 rms finish.

Severe damage including cover or blade replacement can be handled using original welding techniques. However, special attention is required to minimize distortion since the hub and bore are already finished machined. Special clamping fixtures

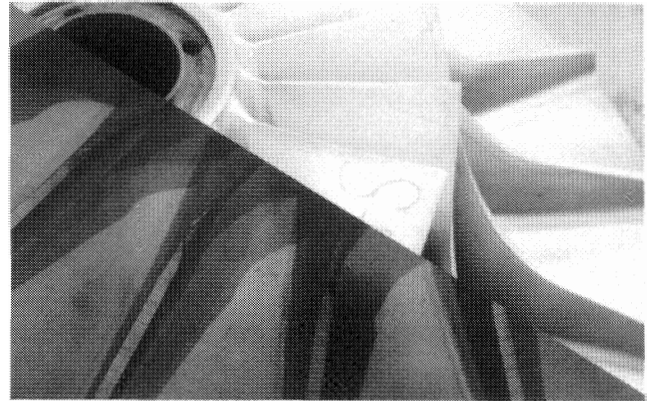


Figure 25. Before and After Shots of an Impeller Restoration. The corrosion damage at the eye and along the blade was built up with a GTAW process. Hand grinding and machine were used to reestablish the original contours.

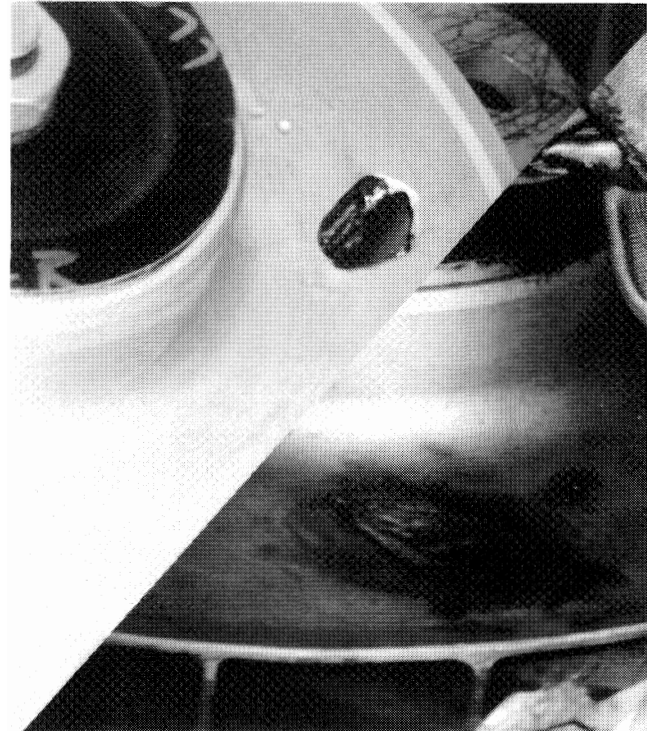


Figure 26. The Cover on This Impeller Was Repaired After a Large Circumferential Crack Developed and a Piece Was Lost. The exposed vane was built back up and a copper strip was used to back up the hole, which was restored completely with weld buildup.

can be designed for use during welding, stress relieving, and machining (Figure 28). Also special consideration must be given to preheating and weld staggering.

#### MATERIAL SELECTION

Another key step in writing a repair procedure is deciding what type of electrode, electrode/gas, or electrode/flux combination to use. To make this determination several issues must be addressed.

The first is to determine what materials are to be welded. If the original specifications, chemistry, and heat treatment are avail-

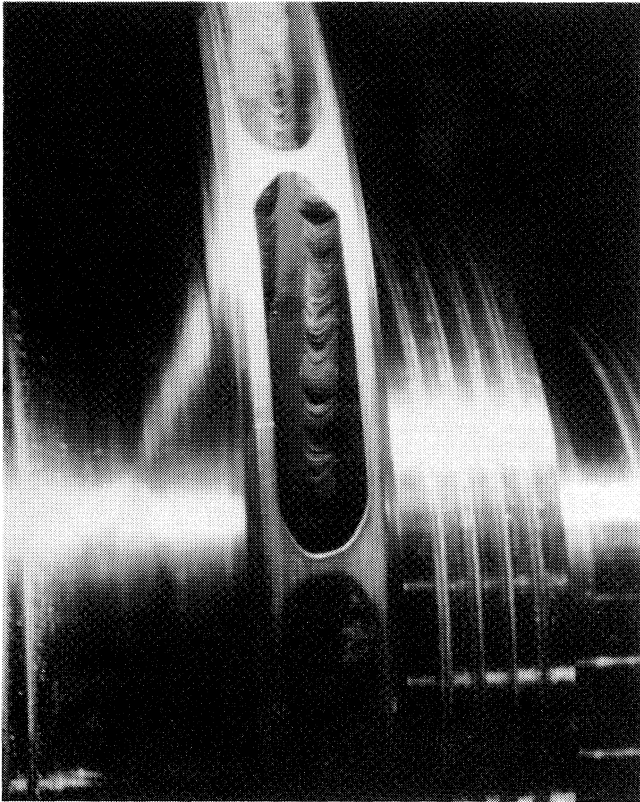


Figure 27. The Outside Finish of This Replicated Impeller Was Good. However, a closer inspection reveals unground fillets in the gas passage. This can result in extreme flow disruption and up to 10 percent flow reduction. The uneven finish and possible undercutting also provide undesirable "stress raisers."

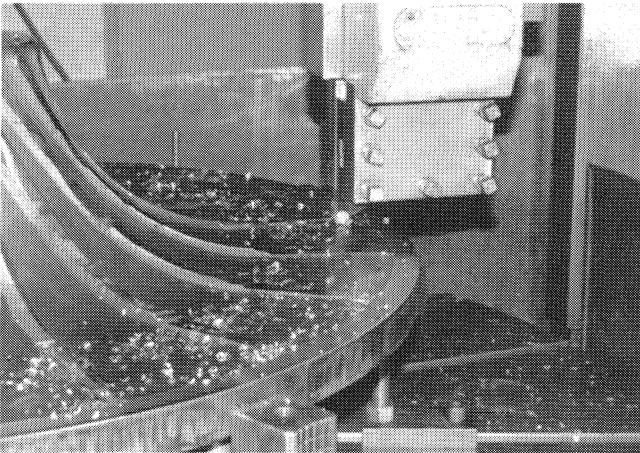


Figure 28. Clamping Fixtures Used to Prevent Distortion While Installing Blades on a Finish Machined Hub.

able, this stage is easy. If not, a thorough analysis of the impeller will be required. This should include separate analysis of the hub, the cover, and the blades. OEMs typically use combinations of materials in their impellers. Two common combinations are AISI 4140 hubs with AISI 4130 blades and 15.5 ph hubs with 17.4 ph blades. Acid etching may suffice or a small sample of each could be processed in a nuclear analyzer. Hardness of each component and the weld metal should also be verified. Portable

electronic hardness testers have made this a viable alternative in difficult to reach sections.

Measure the thicknesses of all the areas to be welded. Thin blade sections are much more likely to suffer "hot cracking" than are thick blades. To remedy these processes, including current polarity and materials, should be selected to allow low heat input and fast travel. Additionally, an electrode with a high ferrite constituent might be selected to reduce cracking in such a case.

Material should be selected that will yield corrosion resistance, tensile strength, ductility, or any other property required of the base materials in the specified service.

*ASME Boiler and Pressure Vessel Code, Section II, Materials* provides a classification system to evaluate and select materials that will yield the desired properties. The code includes separate specifications for acceptance (SFAs), based upon the various filler metals related to specific welding processes.

The ASME SFAs have identical corresponding AWS specifications.

The development of low hydrogen electrodes for the SMAW process has virtually eliminated the problem of hydrogen diffusion and the resulting underbead cracking. However, improper storage and use of the rods will completely destroy their effectiveness. Moisture, which is a potential source of hydrogen, is readily absorbed in these electrode coverings. To ensure a low moisture content, low hydrogen rods should be stored at a higher temperature (400°F) than other types of electrodes. They should also be used immediately after removal from the oven. Exposed rods can be reconditioned by heating them to 180°F for two hours and then baking them at 800°F for an additional half hour.

SAW fluxes are classified in the SFAs by the properties that they promote in the weld metal with a specific electrode classification. Fluxes fall into three general categories: Neutral, active, and alloy. Neutral fluxes contain little or no deoxidizers that might change the weld metal chemistry with variations in arc length. Active flux contains deoxidizers such as manganese and silicon, which provide increased resistance to porosity and weld cracking due to contamination. However, the manganese and silicon can react with these base metals to a varying degree depending upon voltage changes related to the arc length. Alloy fluxes are used with carbon steel electrodes to add ingredients to produce an alloyed weld metal.

Hydrogen diffusion is not common in the SAW process. If present, it is probably a result of moisture contamination in the flux. Granular flux should be maintained at 360°F. Contaminated flux can be reclaimed by heating it to 180°F for four hours and then baking it at 600°F for half an hour.

Material should be purchased that complies with the appropriate SFAs. When qualified manufacturers tag their products with the appropriate SFA classification, this ensures a level of testing and compliance with the code to provide the desired weld metal properties. Material control procedures should include provisions to maintain the appropriate identification with the actual material. Poor identification and inadvertently mixing the wrong flux and wires can produce unacceptable quality or strengths.

## HEAT TREATMENTS

The base metals and the selected welding materials are the key considerations when determining required heat treatments.

Preheating the impeller slows down the cooling rate of the weld site. This is especially important with alloy steels, which develop excessive hardness and brittleness in the HAZ and weld metal, due to rapid cooling through the critical temperature range (approximately 1600°F to 1300°F).

A slower cooling rate of the steel through the transformation temperature allows highly saturated hydrogen to diffuse to the

surface. Trapped hydrogen can exert enough pressure on brittle martensitic crystals to produce underbead cracking (Figure 29).

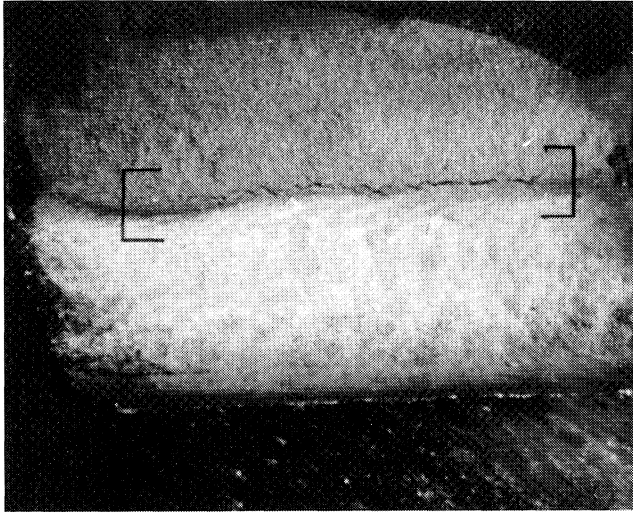


Figure 29. Indications Like This One Are Often Found in the Heat Affected Zone (HAZ) at the Toe of the Weld.

Shrinkage stresses can also be reduced with a slower cooling rate. Localized stresses are better distributed throughout the weld and the weld material tends to relieve itself while still in a hot and, therefore, a more plastic state (Figure 30).

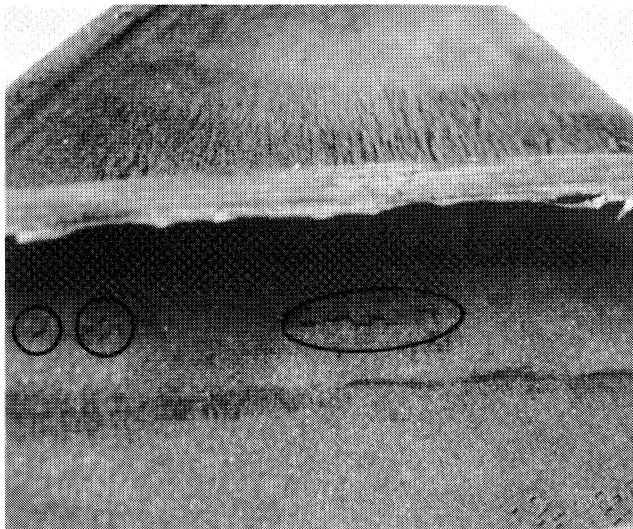


Figure 30. Indications Identified in the Weld Metal.

Preheating the work piece also dries up moisture on the surface and between joints. Moisture can precipitate weld spatter and act as a source of hydrogen. Other contaminants such as oil or cutting fluids can also be burned off during the preheating cycle.

The preheating of impeller weldments is usually accomplished by the use of burner rings mounted to a positioner table (Figure 31). The desired temperature can be monitored easily with an electronic surface thermometer or somewhat less accurately with temperature sticks. The preheat must be maintained

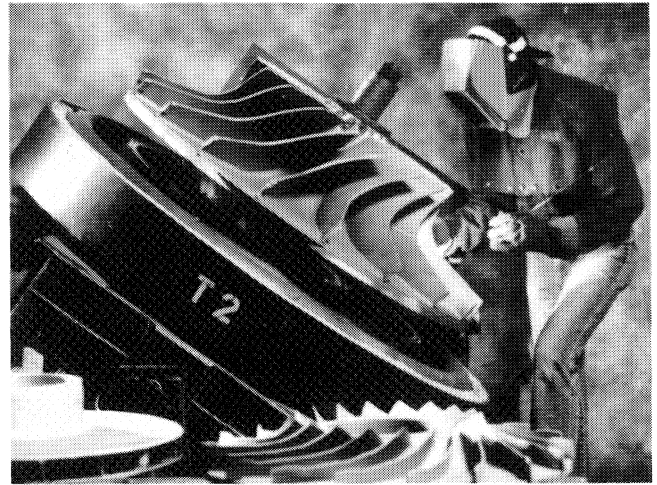


Figure 31. A GTAW Repair on a Weld Positioner Table Equipped with Heat Rings for Preheating.

until all repair welding is complete. In some instances, this may be several days.

Once the welding is complete, and while the impeller is still at the preheat temperature, it should immediately be transferred to the stress relieving oven. Stress relieving is performed in an oven that is capable of a slow controlled heating rate to ensure uniform heating of the impeller (Figure 32). The holding temperature is always below the first critical temperature of the impeller materials. After soaking at this maximum temperature, the cooling should be accomplished in a controlled fashion as well. To ensure that the stress relieving cycle was performed correctly, the oven should be equipped with a chart recorder and the oven should be calibrated on a regular basis. The heat charts can then be incorporated into the QA report.

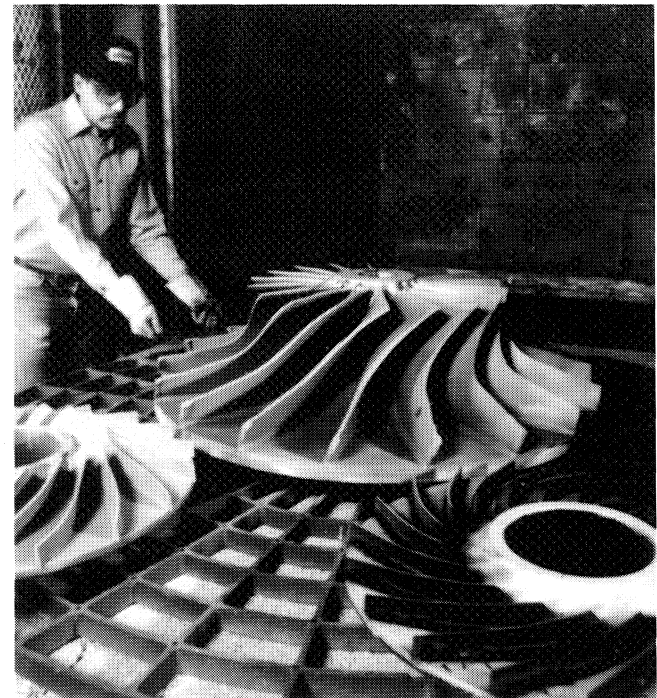


Figure 32. Impellers Being Removed from a Heat Treatment Furnace After the Stress Relieving Cycle.

A typical heat relief cycle for a low alloy steel such as AISI 4130 would be to place the impeller, which has been maintained at the preheat temperature, into an oven preset to 400°F to 500°F. The oven would be programmed to increase temperature at a rate of 150°F per hour until reaching 50°F below the lowest tempering temperature of any of the components of the impeller. Depending on the size of the impeller, it would be held at this soaking temperature from five to ten hours. The cool down would be at the same controlled rate of 150°F per hour. At 500°F, the impeller can be cooled in still air. Typical stress relieving dwell temperature is one hour per inch of maximum material thickness.

The purpose of the stress relieving cycle is to remove the majority of the residual stress developed during the welding or machining processes. These stresses are usually at a low enough level that they will not effect the initial weld quality. However, they can contribute to premature fatigue failures.

Minor weld repairs using the GTAW and SMAW process can sometimes be performed with procedures that do not require preheating. This is acceptable by ensuring a low heat input at the repair site. However, stress relieving is still a prudent step for long term reliability.

A wide variety of information and knowledge is required to successfully repair compressor impellers as well as significant welding, inspection, and testing equipment. An understanding of stress levels and applications, welding techniques and metallurgy has to be brought to each repair with a good understanding of testing and inspection techniques, including their limitations and interpretation. Final impeller overspeed testing after a weld repair double checks the repair and procedures employed. An experienced and well equipped repair facility is recommended for any kind of extensive impeller repair in order to ensure quality, correct application or selection of repair, and appropriate record keeping.

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