

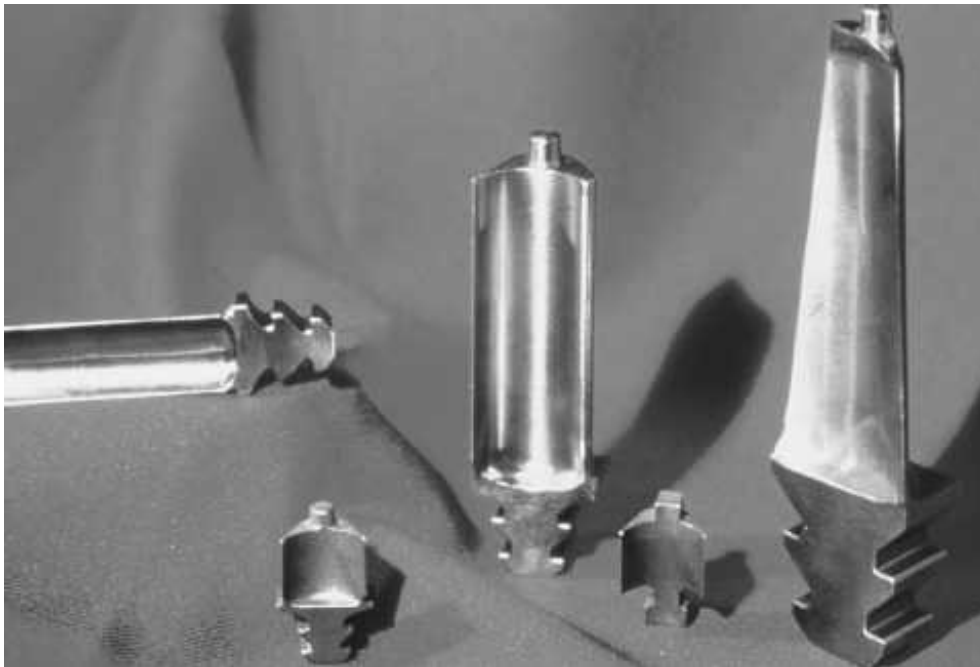
Turbine Blade Construction, Materials, and Manufacture

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3. Turbine Blade Construction, Materials, and Manufacture

The first steam turbines were applied to generators, ships' propulsion systems, and other mechanical drive applications in the early 1880s. In the intervening 130 years, steam turbines have been applied to every conceivable type of service requiring shaft power. Today, steam turbine designs for industrial, marine, and utility services range in size from a few kilowatts in output to multicasing giants producing over a gigawatt. Industrial steam turbines are still used in a wide variety of processes, but today their major applications are as turbogenerators for in-house power and cogeneration and as mechanical drives for pumps, compressors, and fans in the power generation, refining, and petrochemical process industries.

Process drive steam turbines represent a specialized subset of industrial steam turbines that are mainly used by the refinery and petrochemical industries to drive compressors in critical services. These machines range in size from a few kilowatts at the small end to perhaps 100 MW at the large end of the range. They are usually characterized by variable-speed operation (as distinct from the constant synchronous speed of generator drive turbines), sustained operation at high speeds and outputs, and a requirement for high reliability. The varied demands of such a vast application range have given rise to an amazing number of mechanical variations in the design of all turbine components, and especially in the construction details of the rotating blades, a few of which are shown in Fig. 3.1.



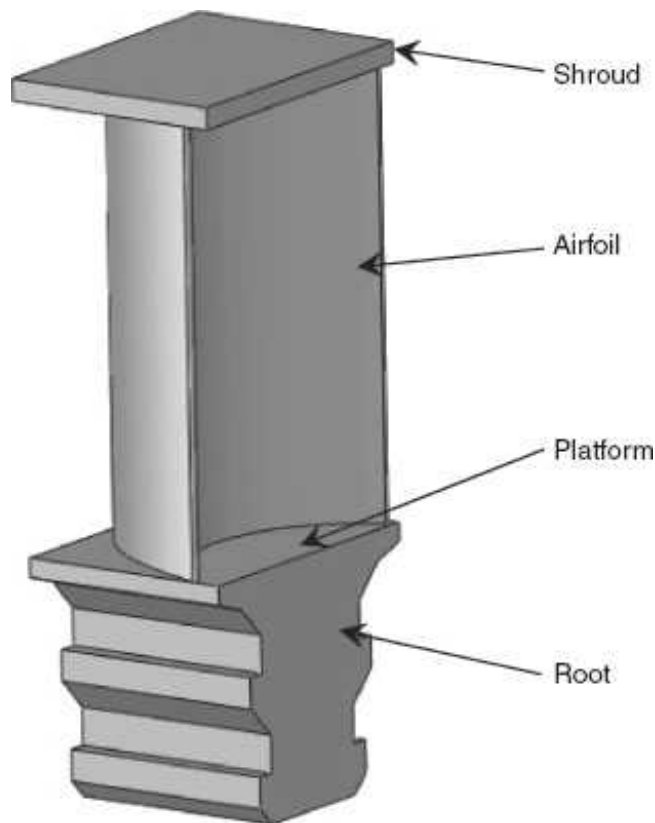
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Figure 3.1. Blades for process drive steam turbines come in a wide variety of sizes, shapes, and styles. (Photograph courtesy of Dresser-Rand Company.)

Fortunately, when the discussion is limited to industrial steam turbines, the variations in blade size and design are manageable. For industrial steam turbines, the range of blade heights under consideration starts around 12 mm (0.5 in) and goes up to a maximum of 750 mm (30 in). In addition, while the number of *potential* materials is extensive, the list of practical, widely used materials is limited to a handful of martensitic stainless steels, titanium, and a few specialty alloys. Similarly, the range of potential processes and tools that can be applied to manufacture turbine blades is very broad, but in practice most blades are produced using only four basic processes—milling, grinding, roll forming, and forging.

A brief overview such as this cannot adequately cover every one of the materials, design variations, and manufacturing processes that are currently employed for industrial steam turbine blading. Surveying the wide variety of designs that are found in successful operation around the globe makes it obvious that many equally good solutions have been developed to meet the demands of any steam turbine application imaginable. Therefore, the inclusion (or omission) of specific features in our discussion should not be interpreted as an endorsement of those features over alternative designs, or of one turbine supplier's solution over another supplier's solution.

While geometric detail dimensions may vary widely, just about every turbine blade can be broken down into a common set of basic features—the airfoil that interacts with the steam flow, the root or disk attachment, the platform that forms the inside-diameter surface of the flow path; and the shroud that forms the outside-diameter flow path surface (see [Fig. 3.2](#)). In addition to these basic elements, some blade designs incorporate specialized structures such as retainers, lacing wires, or auxiliary dampers. These elements may appear as part of monolithic individual blades or as separate component parts that are assembled to form a complete blade system. As we will see, the designer has a wide choice of construction features from which to tailor the blade for a specific application. The final choice of blade design details is often influenced by available machine tools and manufacturing processes, available materials, and relative part cost considerations.



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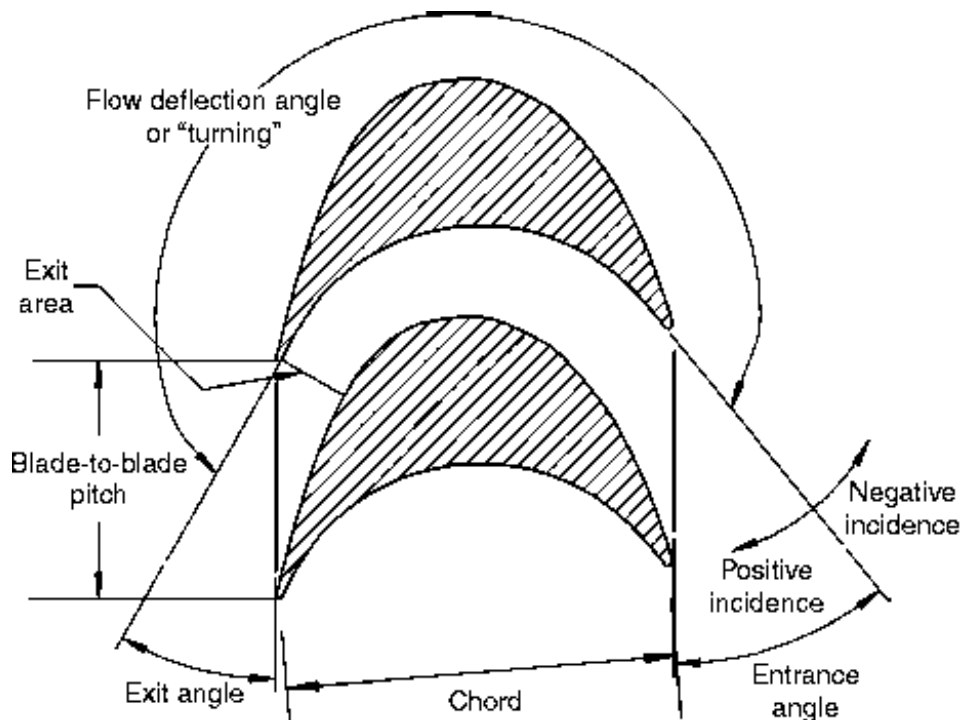
Figure 3.2. Common blade design elements.

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3.1. Airfoils

If we take these common blade construction features in order, it is logical to start with the airfoil, because the airfoil does all the work. The airfoils of the rotating blades represent the only components in the entire turbine that convert energy in the steam to shaft torque and power. Obviously, the performance and reliability of the blades are critical to successful process drives. Critical attributes

of the airfoil include the profile accuracy of the airfoil surface contours, blade-to-blade spacing, and blade path exit area after installed in the wheel. Figure 3.3 illustrates the common terminology applied to airfoils, defining some key airfoil parameters such as chord, entrance and exit angles, exit area, and others.



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Figure 3.3. Airfoil geometry definitions.

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3.1.1. Impulse and Reaction Blades

As noted in Chap. 2, there exists a major division in steam turbine types between impulse turbines and reaction turbines. To review, in pure impulse turbines the entire stage pressure drop is taken across the stationary nozzles, converting heat energy in the steam to kinetic energy at the nozzle exit. That kinetic energy is then transferred to the shaft purely by momentum change (i.e., by turning of the velocity vector only) in the moving blade row, with no significant additional pressure drop.

In contrast, in reaction stages, only a portion of the stage pressure drop is used to convert energy in the steam to kinetic energy in the stationary nozzles, while the remainder of the total stage pressure drop is taken across the moving blades. The momentum change in the moving blades is therefore contributed by conversion of the kinetic energy at the nozzle exit, plus the reaction forces from acceleration of the steam. This acceleration occurs as the remainder of the available stage energy is converted to kinetic energy in the moving blade row. As you might expect, these differences turn out to have important influences on the blade shapes used in each type of machine.

3.1.2. Impulse

Since peak efficiency occurs at low W/V [i.e., at $W/V = (\cos \theta_1)/2$] for impulse stages, the blade speed relative to the steam exiting the nozzles is lower, and the steam enters the moving blade row at a greater angle to the turbine axis (refer to Fig. 3.4a), it must be turned through a greater deflection angle before exiting the moving row. Airfoil sections for impulse stages are characterized by greater turning, and thus a greater total angle, between entrance and exit sides of the moving row. In addition, as we have already seen, to maintain the relatively low W/V values necessary for peak efficiency, the impulse turbine design engineer usually opts for a small number of stages with higher energy per stage, which tends to result in greater steam forces acting on the blade row. Once an airfoil section is selected with the desired total turning and appropriate inlet and exit angles, higher steam loading drives the designer to scale up the airfoil proportions, resulting in fewer, but more robust, blades in the moving row.

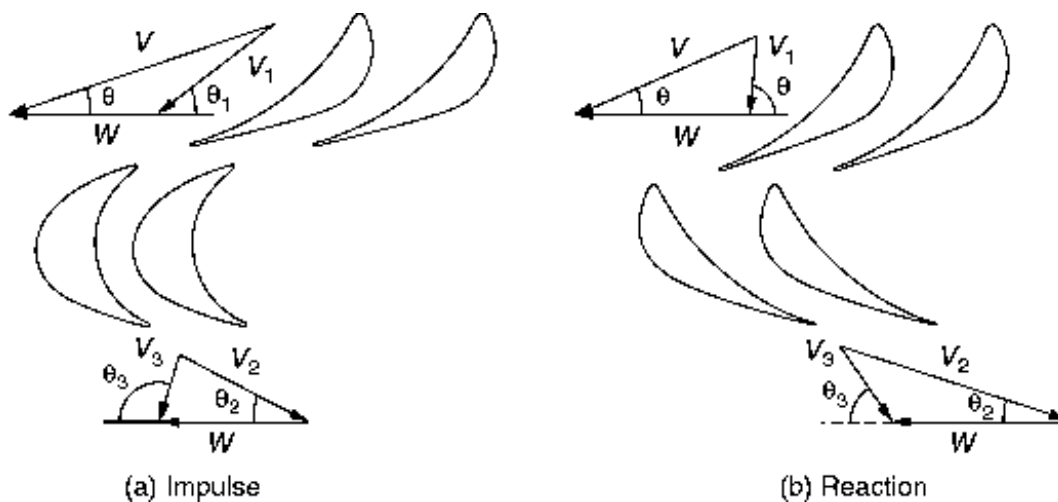


Figure 3.4. Comparison of (a) impulse and (b) reaction cascades and their velocity diagrams.

3.1.3. Reaction

In reaction stages, where peak efficiency occurs at high W/V , blade speed is relatively low compared to the steam and consequently enters the moving row at a relatively small angle to the turbine axis (refer to Fig. 3.4b). In contrast to the case of an impulse turbine, the reaction turbine design engineer usually opts for more stages with higher W/V , and lower energy per stage, resulting in relatively lower steam forces on the blades of each moving row. In counterpoint to impulse stages, reaction stages tend to have a greater number of narrower, less robust blades in each moving row.

Figure 3.5 is comparison of typical turbine cascades for impulse and reaction turbines for the same services. A few additional key features of each turbine type stand out: (1) In the reaction turbine cascade, the stationary nozzle vanes and the rotating blades both utilize mirror images of the same airfoil profile (i.e., symmetrical blading). (2) The impulse stages, due to the higher loading in each stage and on individual blades, are wider than their less highly loaded reaction counterparts. The reaction turbine may be slightly longer than the impulse cascade, but not in direct proportion to the number of stages.



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Figure 3.5. Comparison of impulse and reaction turbine cascades.

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3.1.4. Twisted-Tapered Airfoils

In Chap. 2, the need for airfoils of varying section from base to tip for taller reaction stages and for the low-pressure stages of impulse turbines was explained. Such airfoils are often referred to as twisted or twisted-tapered airfoils. Figure 3.6 shows several versions of blades with twisted airfoils, illustrating a few important aspects of blades with twisted airfoils. From Figure 3.6 it is evident that all these blades have airfoil shapes with a great deal of turning at the base section, and very little turning at the tip, as we noted in Sec. 2.5.2. In fact, the tip section of the tallest blade is very nearly flat in cross section, denoting virtually no turning, only acceleration of the flow inside the moving blade passages.



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Figure 3.6. Tall blades with twisted airfoils. (Photograph courtesy of Dresser-Rand Company.)

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3.2. Roots

Turbine blade roots come in a vast array of shapes, sizes, and attachment geometries. The root is the primary mechanical attachment between the rotating blade and the turbine disk. The root must restrain the blade against centrifugal forces to keep it attached to the periphery of the disk and at the same time transmit steam forces from the blade to the disk to provide shaft power.

Roots in common use can be divided into three broad classifications—dovetail or circumferential roots, axial or fir tree roots, and pinned root attachments ([Fig. 3.7](#)). The turbine design engineer must understand the advantages, limitations, and common applications for each root design.



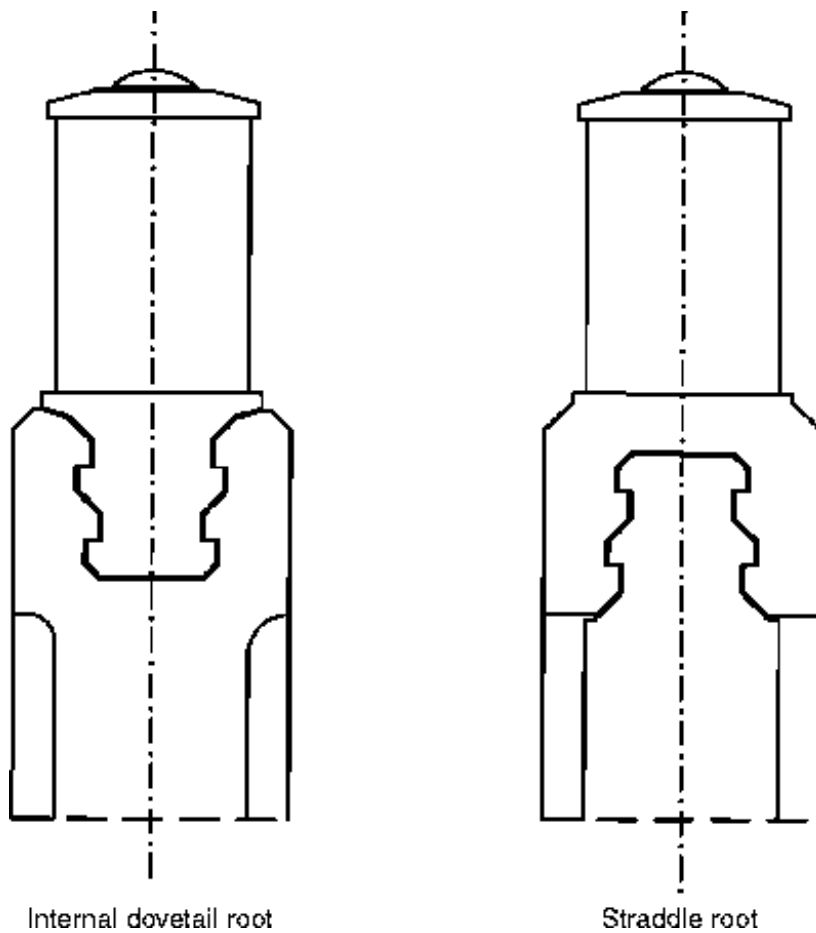
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Figure 3.7. Roots commonly used in industrial steam turbines. (Photograph courtesy of Dresser-Rand Company.)

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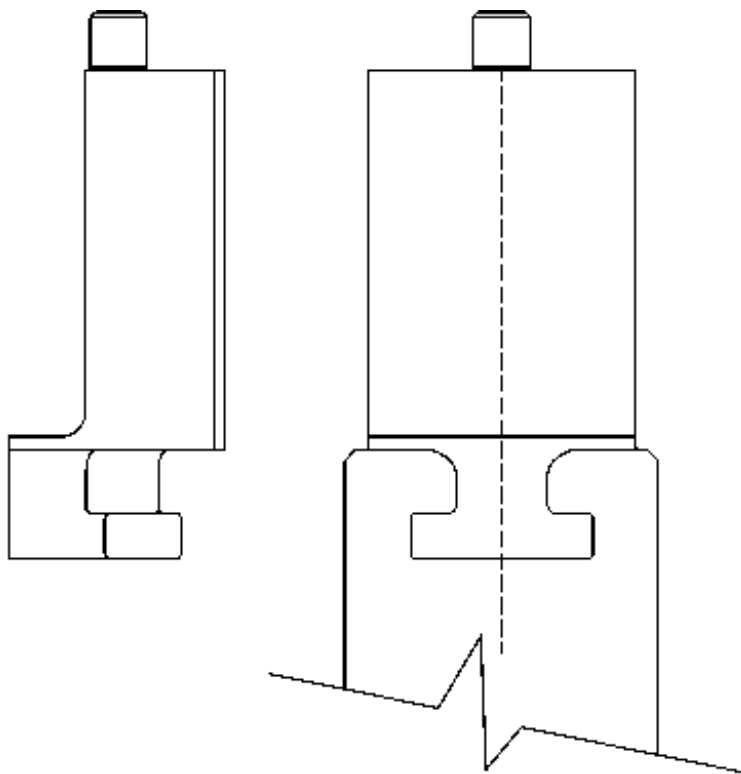
3.2.1. Circumferential or Tangential Dovetail Roots

As their name suggests, circumferential root attachments are circumferential in form. They are the most widely used root form in industrial steam turbines and process drives because they are easily machined on the rotor by turning in a lathe or machining center. The ability to turn the form in the rotor means that the rotor machining is much simpler and less expensive than alternate root forms such as axial fir trees. Figure 3.8 shows the basic configuration of the circumferential root form. The internal dovetail root style and the straddle root style are typical of tangential roots in wide use today. The simplest root form is that shown in Fig. 3.9, which is a basic one-tooth form. A single tooth on each side of the root engages a matching single tooth in the wheel form. Without multiple contact points on each side of the root, the close tolerances between contact surfaces required of multiple-tooth root forms are unnecessary. A single-tooth root form is always less expensive than multiple-tooth root forms.



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Figure 3.8. Dovetail- and straddle-style circumferential roots.



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Figure 3.9. Single-tooth root geometry.

Multiple-tooth forms (refer again to [Fig. 3.8](#)) are used when centrifugal and steam bending loads are moderate to high, resulting in loads that exceed the capability of a single tooth. If the load is shared between additional contact points, both

contact and root bending stresses are reduced, enabling higher powers and speeds than are possible with single-tooth root forms. At the same time, multiple contact points impose more demanding tolerance requirements on the wheel and the blade roots to ensure that the loads are shared more or less equally among multiple contact points.

To ensure load sharing among multiple contact surfaces, blade manufacturers employ matched sets of cutters, produced to very close tolerances, for the blade root and the wheel groove form to ensure correct fit. Figure 3.10 shows typical milling cutters for producing the root form on blades with dovetail roots. The milling cutters are intended to be used in a milling machine or flexible machining center of the type discussed in the section on machining. The wheel root form is machined using a matching form cutter that is procured as a set with the blade root milling cutter to ensure that the tolerances between parts are very closely held. Even with matched cutters, it is sometimes difficult to ensure that the blades and the matching wheel grooves achieve sufficient contact on all contact points. It is common practice to produce one of the components, then fine-tune the setups and cutters for the other component to ensure that the desired contact between the components is achieved. Contact between the mating parts can be inspected and verified using machinists' bluing or a similar dye transfer process to verify the extent of contact between the parts.

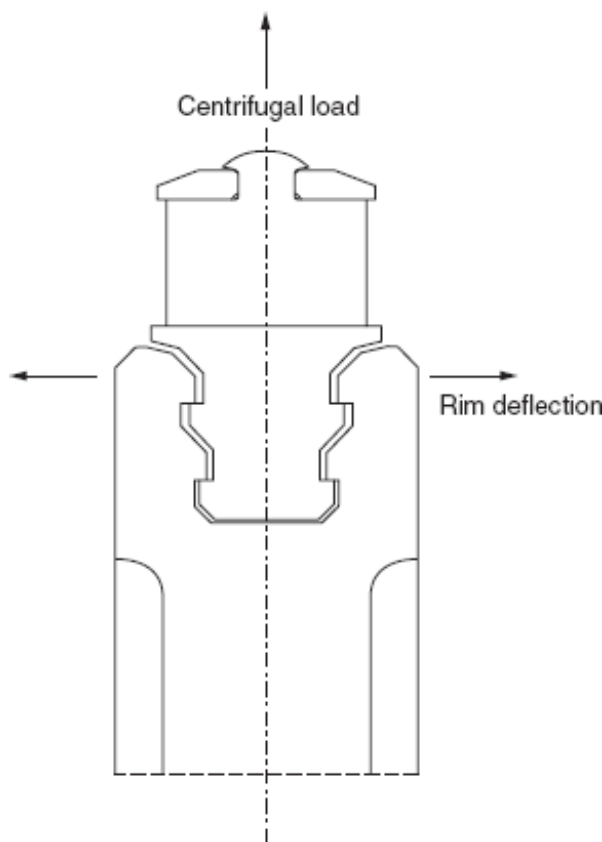


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Figure 3.10. Matched dovetail root cutter set. (Photograph courtesy of Dresser-Rand Company.)

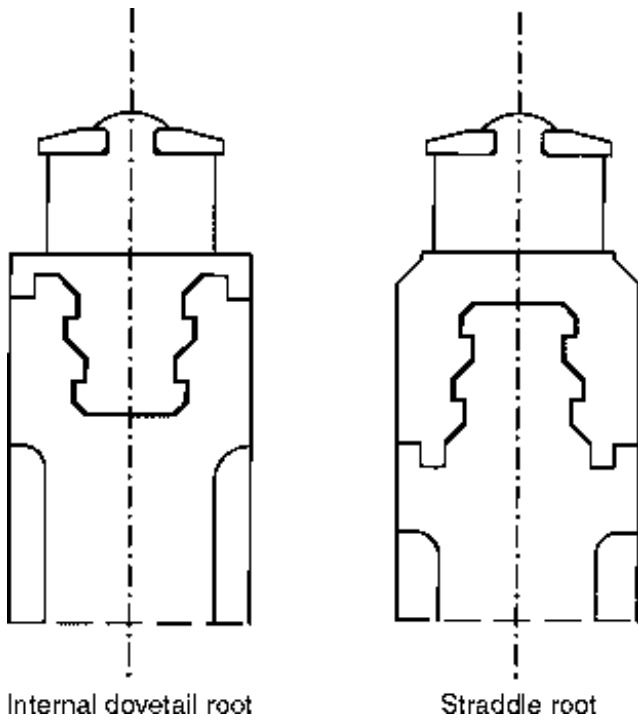
While circumferential roots are perhaps the most widely used type of blade attachment, they have some limitations, especially for units with high speeds and high centrifugal loads, such as, tall last-stage blades or extremely robust control stage blades. In addition to the contact stresses and tensile stresses in the root,

the centrifugal force on the root results in bending deflection of either the wheel rim or the straddle root of the blade. Figure 3.11 illustrates this problem. Wheel rims and blade platforms can be made wider to resist this bending and reduce deflection, but there are practical limits to this solution. The disk stress due to the large mass required at the rim may exceed the disk material's strength limits, or the bladed disk assembly's width may become too great for the available rotor span. Root designs have been created to resist this bending deflection using interlocking forms between the rim and the blade (e.g., Figs. 3.12a and b), that extend the application range of tangential roots to larger blades and higher speeds. Even with interlocking geometry, however, there is a limit where the rim or blade width becomes too wide to be practical.



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Figure 3.11. Rim bending under centrifugal loads.



Internal dovetail root

Straddle root

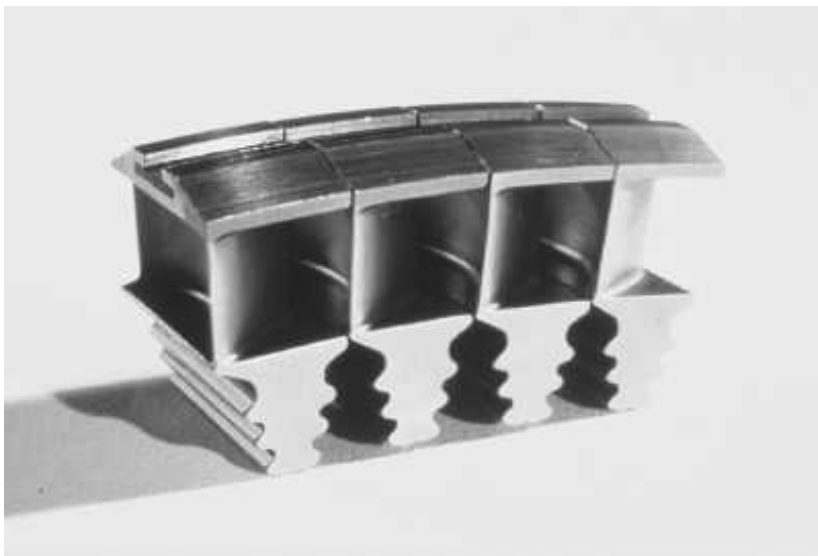
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Figure 3.12. Interlocking platform on dovetail root form to resist rim bending.

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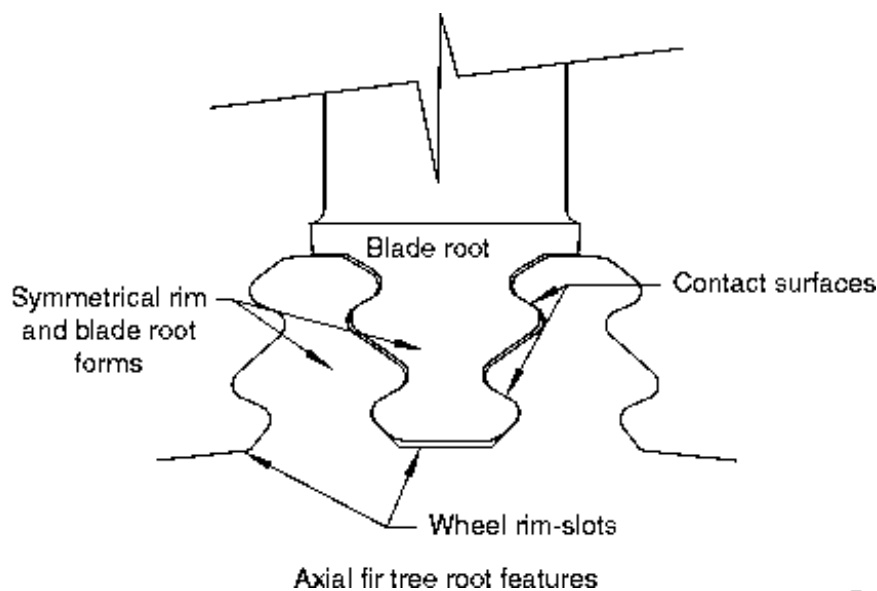
3.2.2. Axial Roots

As the name implies, axial roots consist of profiled slots arranged parallel (or at small angles) to the longitudinal axis of the turbine shaft or rotor, extending completely through the periphery of the disk, with profiles that interlock with matching profiles on the blade root. Figure 3.13 shows a common type of axial root used in many industrial steam turbines. Figure 3.14 defines the important features of the most commonly used form, known as a fir tree root for its resemblance to a Christmas tree.



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Figure 3.13. Turbine blades with axial fir tree roots. (Photograph courtesy of Dresser-Rand Company.)



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Figure 3.14. Fir tree root key features.

For modern industrial steam turbines, practically all axial fir tree roots are produced by milling each slot individually in the turbine disk (Fig. 3.15). This is a consequence of the nearly universal application of integral rotors—i.e., shaft and disks machined from a single large integral forging—to industrial turbine generator sets and process compressor drive steam turbines. (In contrast, most gas turbines with separable disks have axial entry roots that are produced by broaching.) The accuracy of the root profile as well as the angular indexing of each slot to the next must be held to a very close tolerance level. Axial entry roots are more expensive when compared to circumferential roots, but for high-speed, critical service stages they are often the logical choice.



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Figure 3.15. Turbine disks with milled axial roots. Note the narrow space between adjacent disks which limits the diameter of cutters and therefore the width of the root form. (Photograph courtesy of Dresser-Rand

Company.)

Fir tree roots are a good choice for high-speed stages with high centrifugal loads because the blade root and the disk root forms are essentially mirror images of each other. In effect, the imposed loads and stress levels in each of the two parts can be made virtually the same. If the blade and disk materials have significant differences in strength, the width of the disk roots and blade roots can be adjusted slightly to balance the stress levels, recognizing the relative material strength available in each part. Inherent in their design, axial roots also do not suffer from the characteristic bending stress that tries to open up the sides of circumferential dovetail roots. By taking rim bending out of the total and equivalent stress calculations, axial entry roots are able to withstand higher centrifugal and radial tensile loads than is possible with circumferential dovetail roots. Typical applications in high-speed process compressor drives include condensing last-stage blades and highly loaded first-stage blades. Titanium blades coupled with axial fir tree roots are the ultimate choice in last-stage blades for process drives, allowing the use of significantly taller, more highly loaded last-stage blades than are possible with dovetail roots and stainless steel material.

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3.2.3. Pinned Roots

If locking blades and locking spacers can be retained by pins through the blade and wheel rim, it is logical that pins can also be used as the primary retaining mechanism for turbine blades. In fact, pinned roots have been used since early in the development of steam turbines. Pinned roots have been used extensively to retain tall low-pressure blades in medium and large utility condensing turbine generator sets, in addition to low-pressure blades in industrial steam turbines. Proper function of axial and circumferential roots depends upon the precision with which the mating surfaces are produced, requiring very close tolerances to be held on the mating surfaces. Pinned roots, on the other hand, depend on the assembly process. While the wheel and blade root must still be produced to tolerances measured in thousandths of an inch (0.001 in), this is still far less demanding than the precision required for axial or tangential roots where tolerances of ten-thousandths of an inch (0.0001 in) are required.

Pinned roots derive their strength from multiple load-bearing points. Figure 3.16 shows how the root takes the form of multiple projections interlaced between similar grooves on the wheel rim. Each pin shares the load on several shear sections. The area in contact with the pins is roughly equal for both blade and

wheel rim, resulting in roughly equal contact stresses in the mating parts. The designer may adjust the ratio of contact and tensile areas of the blade and wheel rim to make best use of the relative strength of the materials.



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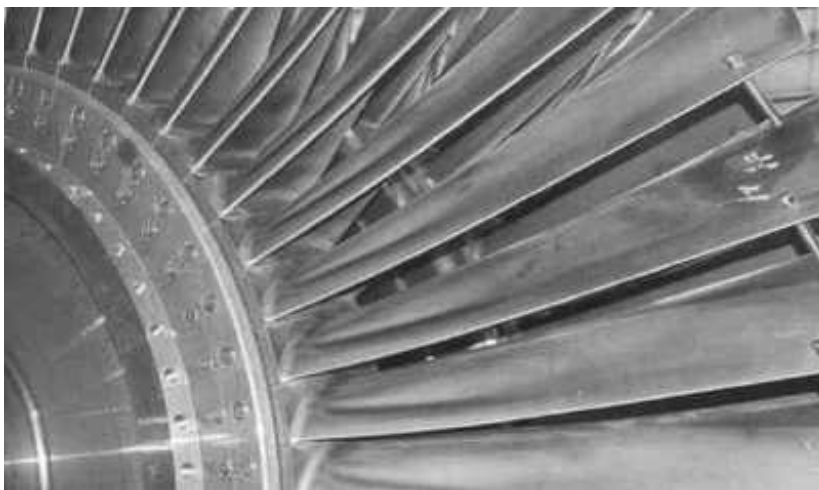
Figure 3.16. Pinned root concept—pins attach blades with one or more projecting forms that match interlacing forms on the wheel rim.

Multiple pins are often used, resulting in even higher load-carrying capability for the overall assembly. As with the retaining pins for locking buckets, a close side-to-side fit between the blade roots and the wheel is critical to ensure that the pins are loaded primarily in shear. Elastic deformation of the blade and disk materials inevitably results in bending stress in the pin. A close fit between the pin and its board minimizes this bending stress and helps to ensure that the centrifugal and steam bending loads are shared between multiple pins. The assembly process is therefore critical to successful pinned root designs.

Because these root forms do not automatically determine the blade location, the assembly process must correctly locate each blade in relation to the turbine rotor at the correct radius to the turbine centerline and with the airfoil stacking axis in the correct angular relation, not only to the rotor but also to adjacent blades in the stage.

Depending on the tools available and the preference of the process engineer, blades and wheel rim may have pilot holes predrilled, or the drilling may all be done in its entirety after the blade is fixtured in its correct location in the wheel. In either case, the final holes are align-reamed through both blade and wheel rim simultaneously at very close tolerance, ensuring proper fit of the pins. To ensure close fit, in some cases the pins may be ground to match the size of individual bores. In many cases, pins that are sized for a slight interference fit must be cooled to facilitate assembly after align-reaming. After align-reaming, the disk, blades, and pins become, in effect, a matched assembly. In this case, if they are removed for any reason, the blades and pins must be reassembled in their original locations on the disk.

Pins must also be positively retained in their bores. Thermal transients during startup or large load changes may result in looseness even in interference-fit assemblies. Coupled with vibration and pressure loads on the wheels, pins will "walk" out of their engagement in the bladed wheel rim if they are not positively retained. A common means to retain the pins involves staking or upsetting the material adjacent to the end of the pins in several locations at each end, to prevent axial movement in the wheel, but they may also be retained by mechanical fastenings of one sort or another. [Figure 3.17](#) illustrates a typical staked pin and root assembly.



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Figure 3.17. Staked pins in bladed disk assembly. (Photograph courtesy of Dresser-Rand Company.)

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3.3. Shrouds and Auxiliary Dampers

Although some process drive steam turbines are built using shroudless, freestanding blades, mainly low-pressure, condensing stages, a majority of blade rows encountered in service will be equipped with shrouds or auxiliary dampers

of some sort.

Shrouds take many forms, but regardless of the form, they are all designed to contribute structural stiffening, damping, or a combination of both to reduce service stress levels and the vibratory response of the blade. In addition, shrouds are often important elements in the aero-thermodynamic design of the stage, forming the outside-diameter surface of the flow path and helping to minimize over blade tip leakage and secondary flows. To the extent that the stage depends on the shroud to reduce the amplitude of vibration or to change the frequency of vibration, they are critical elements for reliable operation of the turbine.

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3.3.1. Riveted Shrouds

Although other designs have important applications, the most commonly used shroud design in service today is still the riveted shroud, where a separate band of material is attached to the tips of each blade's airfoils by one or more peened tenons. [Figure 3.18](#) illustrates the most common type of shroud made from a series of shroud segments, each covering several blades. Shrouds are usually installed to create discrete packets of blades that are tied together by the shroud. The length and number of packets are chosen by the stage designer to modify the vibratory behavior of the bladed disk and to avoid potentially dangerous specific mode shapes and frequencies of vibration for the bladed disk assembly. The importance of packeting and its effect on the bladed disk's vibratory behavior are covered in detail in later chapters.



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Figure 3.18. Photograph of packeted shroud bands typical of process drive turbines. (Photograph courtesy of Dresser-Rand Company.)

Longer shroud segments (so-called long arc shrouds) are difficult to produce, due to the difficulty of installing them without making the holes too large or bending the blades during installation. If long arc shrouds or even a completely shrouded stage is specified by the designer, a double-layer shroud design is often used, made up of two partial thickness bands with their ends staggered or overlapped to create a continuously shrouded stage.

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3.3.2. Integral Shrouds

Unlike riveted shrouds, which are separate parts attached by peened tenons after the blades are assembled in the turbine disk, integral shrouds are produced as integral parts of the individual blades. The complete shroud is therefore formed from the segments of the shroud that are attached to each blade tip. Figure 3.19 shows a turbine rotor equipped with several stages of integrally shrouded blades.



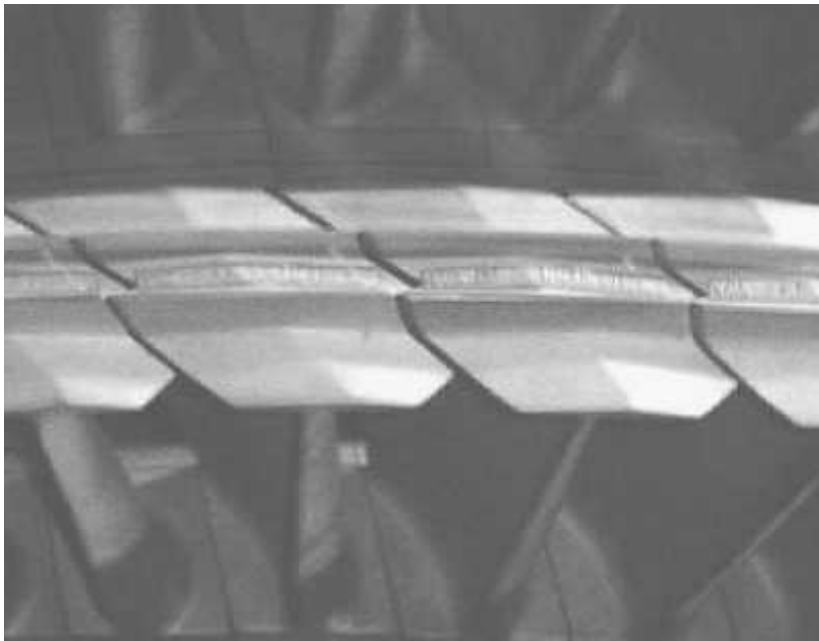
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Figure 3.19. Turbine rotor with integrally shrouded blade rows. (Photograph courtesy of Dresser-Rand Company.)

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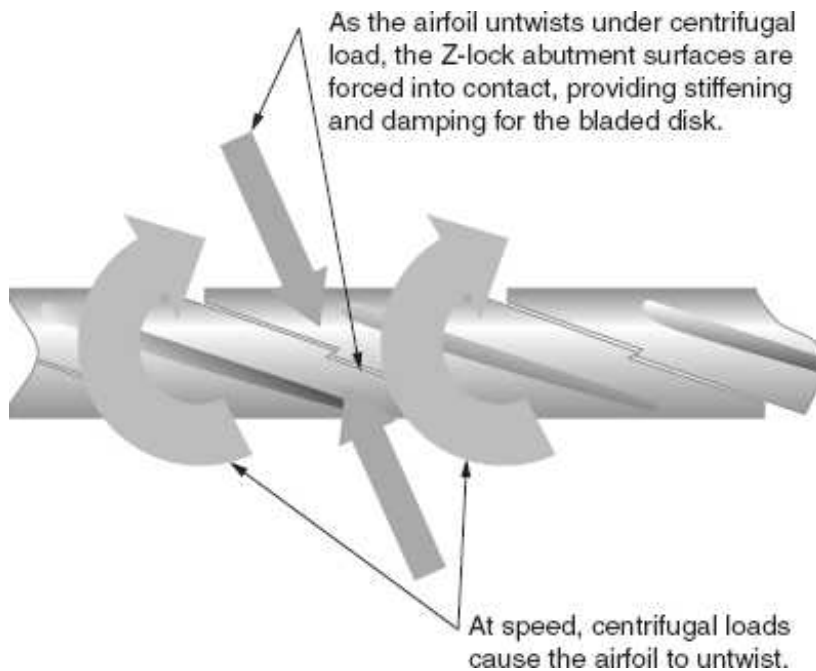
3.3.3. Z-Lock Shrouds

A special version of integral shroud is the Z-lock shroud, consisting of interlocking shroud segments that are loaded against one another in service to ensure contact at the abutment surfaces. [Figure 3.20](#) shows a typical Z-lock shroud as installed in an assembled turbine wheel. Z-locks are almost always used on twisted airfoil sections because they are intrinsically activated by the twisting of the airfoil that occurs with increasing speed, as [Fig. 3.21](#) illustrates. The Z-lock surfaces are oriented to ensure positive contact at the abutment surfaces at speed. To be effective, the positioning and preload of Z-lock shrouds must be carefully controlled. The Z-lock shrouds are almost always used with axial fir tree root designs because the axial root design locates the blades and prevents relative twist between adjacent blades that could lead to variations in contact force, defeating the purpose of the interlocking shrouds.



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Figure 3.20. Bladed disk assembly with Z-lock shrouds. (Photograph courtesy of Dresser-Rand Company.)



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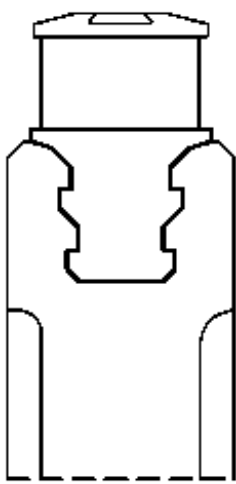
Figure 3.21. Self-actuating design of Z-lock.

The abutment surfaces are often treated with some type of surface modification to prevent wear and fretting on the abutment surfaces. The abutment surfaces may move relative to one another in service, and this rubbing between the surfaces can lead to unacceptable wear of Z-lock contact points. A variety of coatings have been used to combat this wear. A typical surface treatment consists of a Stellite 6 weld overlay, which is easily deposited with either manual or automated equipment and is compatible with virtually all 400 series stainless steel blade materials.

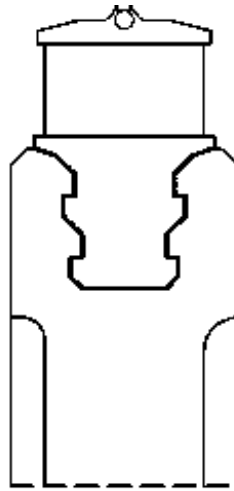
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3.3.4. Auxiliary Shroud Dampers

For additional structural support or to ensure good coupling between adjacent blades with integral shrouds, several types of auxiliary shroud damping devices may be used. One common form is a wire inserted in a slot in integral shrouds and retained either by the form of the wire and the slot themselves or, in the case shown in Fig. 3.22b, by upsetting or rolling the material on either side of the wire.



(a) Friction band shroud with "loose" wire retained by slot form

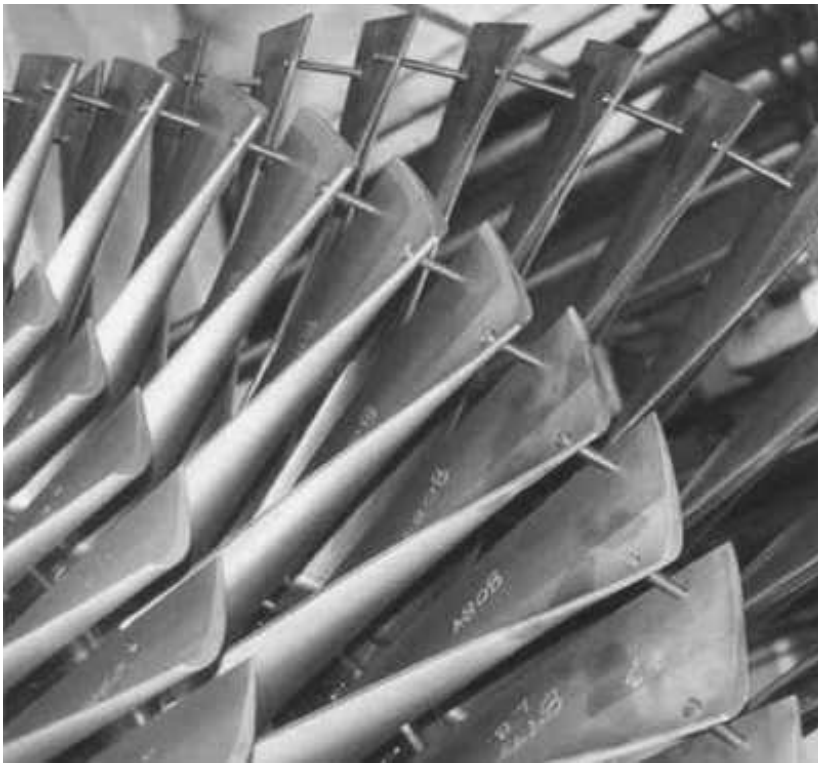


(b) Inserted wire retained by rolling shroud material next to wire

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Figure 3.22. Inserted damping wires in integrally shrouded blades.

For tall blades, high centrifugal loads may preclude the use of continuous shroud. In these cases the blade designer must choose between a freestanding blade or specifying a lightweight damping device that spans the gap between individual blades. The most common device is either a wire that forms continuous 360° ring or individual dampers that span the individual gaps from blade to blade, similar to that shown in Fig. 3.23.



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Figure 3.23. Blade-to-blade damping wires. (Photograph courtesy of Dresser-Rand Company.)

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3.4. Blade Materials

With the wide range of services and the conditions of service that are encountered in the design of industrial turbines, one might expect an equally broad range of materials that could be specified for turbine blades. In fact, blades for modern industrial turbines and process drives, regardless of the original manufacturer, are almost all manufactured from a rather small set of widely used materials. An ideal turbine blade material has both high tensile strength and high fatigue strength. In addition an ideal blade material is corrosion-resistant and erosion-resistant, exhibits high ductility, is easily formed and machined, is widely available from multiple sources, and can be obtained at reasonable cost.

The high rotational speed of modern turbines means the blades are subject to large centrifugal forces, in addition to the potentially high repetitive bending forces imposed by the steam. One would therefore think that high tensile and fatigue strengths are the paramount requirements for turbine blades. While strength is a critical attribute of turbine blades, a high degree of ductility is also a critical property in any good blade material. In spite of closely held dimensional tolerances and careful assembly, the mating surfaces of blade and disk root structures never share perfect contact. On initial start-up therefore small zones of plastic deformation occur that result in improved contact between mating

surfaces. This process is so critical to successful long-term reliability that turbine design engineers are willing to sacrifice some degree of tensile strength in return for improved ductility.

Nearly all steam turbine blade materials in common use are wrought materials. Webster's Dictionary defines *Wrought* as "worked; to fashion or create a useful or desired product by expending labor or exertion on" (see Merriam-Webster Unabridged). Force is applied by various forming processes such as forging, pressing, and rolling to reduce large sections to smaller shapes. In the process, material properties are changed and enhanced. Most forming processes also create directional variations in material properties as a result of the process. Forging and rolling operations tend to align and elongate the metal's grains in the direction of maximum elongation of the material and to narrow the grains in the direction of maximum reduction in section. Wrought materials usually exhibit some degree of directionality in properties such as tensile (and fatigue) strength, modulus of elasticity, and Poisson's ratio. Designers take advantage of this directionality by aligning the long axis of the grains with the direction of the maximum alternating bending stress, for example.

Stocks of blade materials are available in a variety of forms, including hot-rolled and cold-rolled bar stock, forged bars, as well as "bar" stock that is actually produced by reducing (cutting or slitting) larger forms into smaller sizes. This last approach can significantly reduce the cost of blade material, but the designer must be aware of how the directionality of rolling and forming affects the material properties. For most forgings and bar stock, the directionality is obvious from the shape of the material. For some forms, such as machining blanks that are cut from larger bars, it is important to keep track of the grain's direction to ensure that the axis of the material's grain flow coincides with the radial axis of the finished blades.

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3.4.1. Stainless Steel

Type 403 and 410 stainless steels are among the most widely used materials for steam turbine blades. These alloys are very similar in chemical composition. Both are martensitic stainless steel alloys that can, through appropriate heat treatments, exhibit strength levels covering a wide range, depending on process variables such as the quenching and tempering temperatures, among others.

As used in blade applications, these materials are usually heat-treated to moderate strength levels, allowing the material to retain relatively high ductility, in the range of 20 percent or greater. This combination is ideal for turbine blades that are subject to high centrifugal and bending loads. The ductility is a very important characteristic as it allows, e.g., root contact surfaces to undergo slight plastic deformation to better share service loads, without the risk of cracking or failure. This same property gives turbine blades the ability to absorb minor damage in service from erosion, rubs between stationary and rotating parts, and foreign object damage without failure.

Microscopic material defects and inclusions well known to reduce fatigue strength act as starting points for cracks in steel materials, and therefore have a severe impact on the reliability of turbine blades. To avoid these problems, special care must be exercised to ensure that blade materials are as defect-free as possible. Vacuum melting processes produce "cleaner" steels than air melt processes. While single vacuum melt materials are widely used, for maximum reliability, the use of double vacuum melt or VIMVAR (vacuum induction melt, vacuum arc remelt) material is recommended for all critical process drive blading.

Type 403 stainless steel exhibits a significant decrease in usable material strength at elevated temperatures. Because of this, turbine design engineers often specify alternate materials for high-temperature stages. Type 422 SS is often specified for high-temperature, high-pressure stages because of its higher tensile strength and ultimate strength at high temperatures, as well as higher creep resistance at high operating temperatures. Type 422 is not commonly used for low- and moderate-temperature applications, since it is more expensive than 403 or 410, and the ductility of 422 at low temperatures is significantly less than either 403 or 410 SS materials. However, at service temperatures above 850°F, its ductility is comparable to those of 403 and 410 SS. Typical applications include first-stage blades in high-temperature applications, and as an alternate to 403 and 410 SS in stages with moderate service temperature and high stress levels.

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3.4.2. Titanium

Titanium is an excellent material for low-pressure steam turbine blades. The usable strength of titanium falls in a similar range to that of 403 and 410 SS, but its density is only 60 percent of that of commonly used martensitic steels. When Ti is substituted for 403 SS, for example, the centrifugal stress is reduced due to the lower density. With reduced stress level from centrifugal load, the blade is

able to sustain higher steam bending stresses without exceeding the material's maximum allowable principal stress or shear stress criteria. Taller blades, with increased flow limits, are possible for high-speed applications.

The ratio of titanium's elastic modulus to density (E/ρ) is very close to the ratio exhibited by 403 and 410 martensitic stainless steels, which exhibit an elastic modulus in the range of 29 to 30×10^6 psi. As noted above, titanium's density is only 60 percent that of stainless steel. Coupled with an elastic modulus of approximately 16.8×10^6 psi, this results in a ratio of elastic modulus to density that is virtually the same as that for 400 series martensitic stainless steel. This produces fundamental blade frequencies and mode shapes that are nearly identical when the same blade geometry is produced in either titanium or 400 series stainless steel. In many cases therefore titanium can be treated as a direct substitution for stainless steel in highly stressed stages. This characteristic provides an opportunity, when considering upgrades or unit reapplication studies, to significantly increase the turbine's speed and output while retaining the original rotor. Titanium is, however, limited to low- and moderate-temperature applications, so it is not a substitution candidate for stages with high operating temperatures.

For LP stages, titanium's greater inherent resistance to water droplet erosion also means that it can be applied at higher erosive potentials than stainless steels without additional erosion protection. In many applications, eliminating erosion protection treatments offsets a significant portion of titanium's higher raw material cost.

Ti-6Al-4V is the most commonly used alloy for blades, although other alloys in the Ti-6Al family have also been used. It is available in a range of forms and sizes. Smaller titanium bars are often stocked by metals suppliers, but larger sizes may require longer lead times.

Table 3.1 compares properties of the most common blade materials. In general, the cost of finished blades increases as you progress from 403 and 410 SS to 422 SS, and finally to Ti, because of increasing raw material cost, coupled with higher forming, machining, and finishing time and costs. As one would intuitively expect, stronger materials are harder to machine and therefore more costly to process. (The reader is cautioned that the values in this table are average handbook values, and the properties of specific materials and particular heats of a specific material may vary significantly depending on the actual process parameters.)

Table 3.1. Comparison of Common Steam Turbine Blade Materials

	403 SS	410 SS	422 SS	Ti-6Al-4V
Tensile strength, ultimate, ksi	110	120	150	120
Tensile strength, yield, ksi	85	105	125	110
Elongation, percent	23	21	19	15
Elastic modulus (10^6 psi)	29	29	28.9	16.8
Hardness (Brinell)	170	237	275	319
Relative machinability, percent	100	75	62	55

3.4.3. Other Blade Materials

While 403 and 410 SS are the most widely used stainless alloys, there are a few materials that see limited use in process drives for special situations. Austenitic 300 series SS materials have been used in very limited numbers of specialty turbines, particularly in applications where the steam is likely to contain corrosives. The strength of most austenitic stainless steels cannot be increased by normal heat treatment processes, so the material can only be applied at very low stress levels. A286 alloy is special case of an austenitic superalloy that can be strengthened by precipitation hardening. This property makes A286 an appropriate choice for blades and disks in process hot gas turbines operating at temperatures of 1000°F and above, and it has been applied in some steam turbines operating at high temperatures.

Other superalloys have also seen very limited application in steam turbines. IN718 can be used as an alternate to 422 SS in very highly loaded, high-temperature ($\approx 1000^\circ\text{F}$) first-stage blade applications. IN718 is an excellent material for high-temperature applications, but its significantly higher raw material cost and difficulty in machining limit its application to special cases.

There are also some alloys that see limited use in low-pressure turbine stages because they exhibit good erosion resistance without additional surface treatment or overlays. Vasco M252, for example, sometimes called *Jet Hete*, was one of the earliest superalloys developed for gas turbines. It is now sometimes used for last-stage blades in erosive applications. It has the advantage of higher inherent strength than either titanium or 400 series stainless steel, and it exhibits a high degree of inherent erosion resistance. It has been used successfully in last-stage blade applications without additional surface treatments, but its use is limited by its higher material cost and high relative machining difficulty.

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3.4.4. Material Forms

Blade materials are available in a variety of raw forms. In practice, the manufacturing process chosen for a specific blade row determines to a very large extent the required material form. The vast majority of blades for process compressor drives are fully machined from bar stock. Some variations on this process include the following:

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3.4.4.1. BAR STOCK

The most common material form used in blade manufacture is bar stock. The 403, 410, and 422 martensitic stainless steels are all widely available as both hot- and cold-rolled bar stock. Almost any square or rectangular shape up to an approximate 3 in width can be procured as bar stock. Bar stock shapes are created by rerolling larger shapes or billets to smaller size, ensuring that all the material is subject to significant deformation, resulting in uniform properties and ensuring that the resulting material has the desirable properties of a wrought material.

Blanks for blade machining are often produced by cutting or slitting larger material forms to produce smaller blanks of appropriate size. Since many of the desirable properties inherent in wrought material depend on the directionality of

the final forming process, it is critical that the resizing process take this into account to ensure that desirable directional effects are preserved in the stock used to produce blades.

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3.4.4.2. FORGED BARS

The center of large (greater than 3 in) bar stock may not experience the degree of deformation necessary to impart the material enhancements expected from wrought materials. A material form known as *forged bar* is often used to provide improved control of properties in completely machined blades requiring stock with thickness greater than about 3 in.

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3.4.4.3. ENVELOPE FORGINGS

Envelope forgings are rough forgings of the airfoil with 1 mm to 3 mm stock allowance over the entire surface, depending on the size of the blade and the specific machining process to be used. Strategically placed blocks of material is provided in the forged shapes from which roots, tenons, and shrouds are formed by machining. Additional material is often added to provide temporary fixturing points or lugs to facilitate stock holding on the machine tools. These auxiliary fixturing points are removed once they have served their purpose. Due to the relatively relaxed tolerances required in the forging, envelope forgings require less expensive tooling and per piece cost than net shape forgings.

Envelope forgings that are later fully machined have largely replaced the use of net shape airfoil forgings in small and medium steam turbines. Forgings are often used for medium to large blade sizes to minimize total machining times. Envelope forgings require less expensive tooling than net shape forgings and can be produced on a wider range of forging presses. Lead times for envelope forgings are typically about one-half those for final net shape forgings. Although envelope forgings must be completely machined, the cost of finished blades is similar to that of net shape forged blades, because the total amount of material removed is minimal. Blades produced from envelope forgings, because they are fully machined, can be produced with finer dimensional tolerances on the airfoil contours, which in turn produce closer control of stage areas, more accurate surface profiles, and consequently improved aerodynamic performance. Figure 3.24 illustrates an envelope forging and the finished blade produced from that forging.



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Figure 3.24. Example of envelope forging and completed blade.

(Photograph courtesy of Dresser-Rand Company.)

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3.5. Manufacturing Processes

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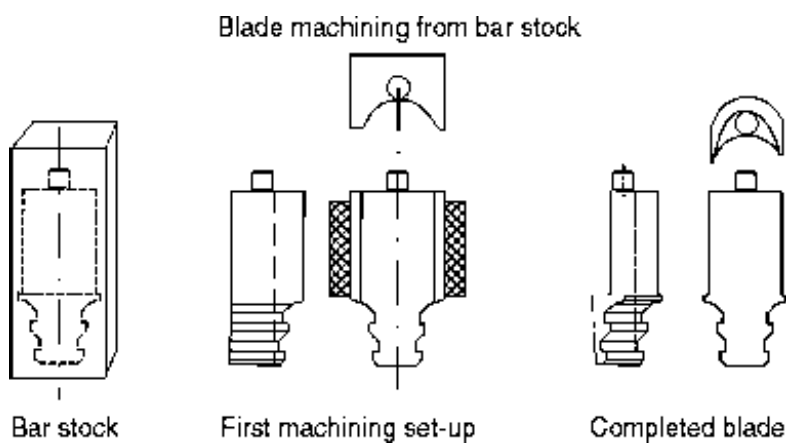
3.5.1. Blades with Constant Section Airfoils

Blades with constant section airfoils are usually fully machined from bar stock. The airfoil surface is produced by a milling process in which the airfoil contour is formed by a milling cutter that traces the airfoil contour on a CNC machining center. Figures 3.25 through 3.28 illustrate some of the typical steps involved in production of a turbine blade from bar stock. Some variations on this process include the following:



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Figure 3.25. CNC machine tool for blade machining. (Photograph courtesy of Dresser-Rand Company.)



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Figure 3.26. Blade machining steps.



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Figure 3.27. Bar stock "blank" for turbine blade. (Photograph courtesy of



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Figure 3.28. Completed turbine blade. (Photograph courtesy of Dresser-Rand Company.)

1. For blades with riveted tenons, the airfoil is formed by tracing around the entire airfoil shape (pressure and suction surfaces) with a side milling cutter. For maximum accuracy and speed, the largest cutter diameter is chosen that can produce the minimum concave radius of the pressure surface. The blade is then cut to length and the tenon (round or kidney) is produced on the blade tip by milling.
2. For blades with flat-top integral shrouds, the cutter that forms the airfoil must also incorporate the fillet radii at the junction of the airfoil with the top of the platform and the underside of the shroud.
3. When a slant-top integral shroud cannot be avoided, the area under the shroud must be finished using a ball end mill. This is a time-consuming and expensive process, since the mill cannot exceed the diameter of the fillet radii between the airfoil and underside of the shroud.

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3.5.2. Blades with Taper-Twisted Airfoils

Twisted and tapered airfoil sections are used in reaction turbine stages, including the low-pressure stages of impulse turbines. The airfoil section varies continuously from the platform to the blade shroud or tip, to account for the changes in relative velocities of blade and steam flow.

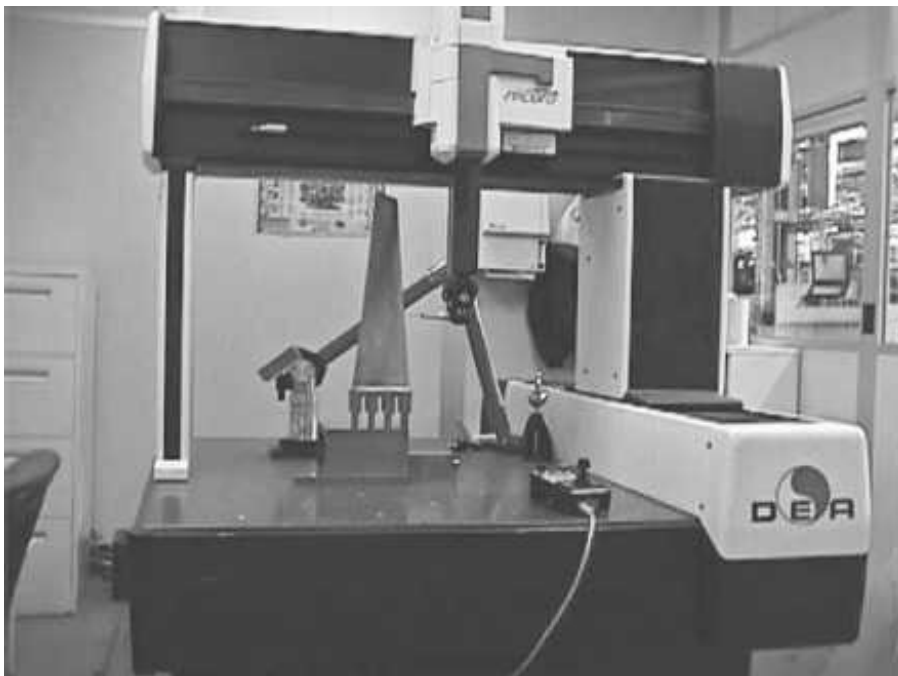
Twisted airfoil sections are produced by three main methods. For small (a relative term) blades the airfoil may be produced completely by machining from bar stock. The airfoil surface is produced by a milling process in which the airfoil contour is by a milling cutter that traces the airfoil contour under CNC. A typical machining process uses a four-axis or five-axis milling machine or machining center equipped with a ball end mill to trace the three-dimensional surface of the airfoil. This machining process produces a high-accuracy surface, but leaves small ridges of material where successive passes of the milling cutter overlap.

These ridges are removed by a subsequent grinding and polishing process to reach the final airfoil shape. This may be a manual process using belt sanders and polishing wheels, although industrial robots are taking over this process to produce a more consistent result. The choice of manual vs. robot is driven by the number of blades to be produced, i.e., higher quantities justify robot setup and programming. This process is capable of producing blades with minimal dimensional tolerances.

Airfoil surfaces may also be produced by forging processes. Envelope forgings are formed to the airfoil contours with several millimeters of excess stock. This stock is removed by the same machining and polishing process used for bar stock.

The forging process can also produce an airfoil forged to net shape, requiring only grinding and polishing to finish the airfoil. Machining stock is provided for root and tip machining operations.

The airfoil is numerically modeled by defining a series of sections at regular intervals along the stacking axis from platform to shroud. Although as few as four sections can be used, a smoother and more accurate profile can be obtained with more sections. Ten sections, defined by the profiles at 11 stations, are typical. The points that define these sections are used to create a three-dimensional spline representation of the airfoil surfaces. The same solid model created by these boundaries is used for engineering analysis (e.g., aero and stress), and then to program the CNC machining center and the CMM (as illustrated in [Fig. 3.29](#)) for automated inspection of the finished blade.



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Figure 3.29. CMM inspection of blade with twisted airfoil. (Photograph courtesy of Dresser-Rand Company.)

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3.6. Erosion Protection—Condensing Stages

Low-pressure stages in condensing steam turbines present another special case that the designer must consider. For condensing turbines, power produced in the last stage is a strong function of the exhaust backpressure. Low-pressure stages in condensing turbines, and in the last stage in particular, are other special cases that the designer must recognize and contend with. The term *condensing* is used for turbines with subatmospheric exhaust pressure, where the exhaust flow discharges directly to the service condenser (a heat exchanger that condenses the steam). The liquid condensate is then reused as feedwater, recirculating through the system many times.

The minimal losses of water for this closed system are replaced by makeup water that is demineralized before entering the system. In a closed system, control of water chemistry is critical, to prevent the buildup of harmful constituents.

Dissolved oxygen, e.g., is corrosive, affecting not only the turbine materials, but also the boiler, plant piping, and any other equipment in contact with the steam. Other potential contaminants include minerals such as silica that may accumulate on turbine blades and of nozzles, reducing flow areas and ultimately reducing machine capacity. So why is this important to the discussion?

In condensing turbines, as the enthalpy of the system of steam is reduced, some of the steam may condense, so that flow through the low-pressure stages is actually composed of two phases, saturated steam and liquid condensate. Water-soluble minerals, chemicals, and gases tend to concentrate in the liquid fraction, which may result in very high concentrations of contaminants in the liquid phase. These contaminants may be corrosive or erosive, leading to damage in low-pressure turbine components. As steam starts to condense in the low-pressure stages, centrifugal force causes the raw condensate to collect at the outside periphery of the flow path. As the water condenses on the surfaces of the stationary flow path, droplets coalesce into water that streams from the trailing edge of the nozzles directly into the path of the moving blades. The liquid droplets move at much lower velocity than the vapor phase, so the leading edge of the blades smash into the slow-moving liquid droplets at high speed. This can be highly erosive to untreated blade materials. As a minimum, the loss of blade material to erosion leads to performance degradation and, in severe cases, compromises the mechanical integrity of the blade. Since velocities are greatest near the tips, the most severe erosion occurs in the outer third of the airfoil and the shrouds, if they are present. To combat erosion, a wide variety of treatments have been devised to combat water droplet erosion in low-pressure turbine stages.

For a given unit, the potential of erosion increases with increasing blade speed and with the amount of liquid phase present. In general therefore large tip diameters and higher rotational speed increase susceptibility to erosion. This is an important subject in turbine design, and over the years, many researchers have worked to characterize the erosion problem and have developed a number of approaches to predict erosion potential based on stage operating parameters. Virtually every turbine manufacturer has developed their own empirical erosion protection guidelines based on field experience with their particular stage designs. In general, erosion is dealt with in two main ways—remove the water from the flow path and use erosion-resistant materials or material overlays.

Untreated 403 or 410 stainless steel is quite susceptible to liquid droplet erosion and should only be used in low-speed stages with relatively small amounts of liquid condensate present. However, since these materials are strong, durable, and widely available, a variety of surface treatments have been developed to improve their erosion resistance.

One of the simplest approaches is flame hardening of the leading edge. In this process, an oxy-fuel torch heats the leading edge of the blade, immediately by a spray quench. The process is usually automated to ensure repeatability in heating and quenching for all the blades in a stage set. The objective in the flame hardening process is rapid heating of the surface area to be protected, followed by rapid quenching. This results in a thin layer of stronger, harder material on the surface with a core of ductile material underneath. Flame hardening is quite effective for stages with moderate erosion potential. Where it is appropriate, it has significant advantages over more aggressive treatments. Since the ductile core is maintained in all but the thinnest blades, flame hardening is a low-risk process. Flame hardening is inexpensive and requires short production cycle times, and the retention of the ductile core makes it a very low-risk process. If erosion in service proves to be a problem, there are repair techniques available to salvage blades with moderate erosion damage and to upgrade erosion protection in future operations.

However, flame hardening is not applicable to all blades. Very thin blades, are susceptible to through-hardening, which completely eliminates the ductile core. And conventional flame hardening may not provide adequate erosion protection in stages with high erosion potential. One alternative in such cases is laser hardening. Laser hardening relies on the same concept as flame hardening, except that it uses a high-powered laser to heat a very thin surface layer very rapidly, and it quenches the hot metal just as quickly, resulting in a harder but thinner layer at the surface for conventional flame hardening, and the harder surface layer protection provides in stages with high erosive potential.

One of the earliest approaches to prevent leading-edge erosion was to undercut a portion of the leading-edge contour and insert a thin layer of hard, erosion-resistant material such as Stellite or similar alloys. In this process a thin layer of Stellite strip or bar stock is attached to the undercut by brazing or welding. The Stellite bar is then blended to using abrasive belts or grinders to restore the desired airfoil surface contours.

Stellite is extremely erosion-resistant, but it is common to observe blades with long service where the untreated blade material adjacent to the Stellite inserts has eroded away around and even underneath the insert. Stellite bars are still widely used today, but more common today is a weld overlay process to deposit a layer of Stellite that more closely conforms to the surface of the blade. This reduces the total amount of material required and reduces the time and cost of blending the Stellite overlay to the final airfoil profile. This process permits its use

on many blades that are either too thin or have contour changes too sharp to use a flat insert. Incidentally, the same process can also be used to build up and restore eroded blade surfaces on blades exhibiting erosion damage after service.

Some available blade materials in service today are also naturally resistant, to a greater or lesser extent, to water droplet erosion. Titanium blades, as we have already noted, are used in many high-speed process drives, since the material has strength similar to that of stainless steels but weighs only 40 percent as much. Titanium is also significantly more erosion-resistant than 400 series stainless steel and is therefore used without added surface treatment in many industrial process drive turbines. Recent experience shows that untreated titanium may still exhibit significant erosion in some conditions, and titanium stages with high erosion potential may still require additional surface treatment. Titanium is compatible with several PVD and CVD coatings that can be used to improve erosion resistance.

As we noted in Sec. 3.4.3, there are also specialty alloys, such as Vasco M252, that are used in a limited number of low-pressure turbine stages because they exhibit good erosion resistance without additional surface treatment or overlays. To reiterate, Vasco M252 has the advantage of higher inherent strength than either titanium or 400 series stainless steel. It exhibits a high degree of inherent erosion resistance and has been used successfully in some last-stage blade applications without additional surface treatments.

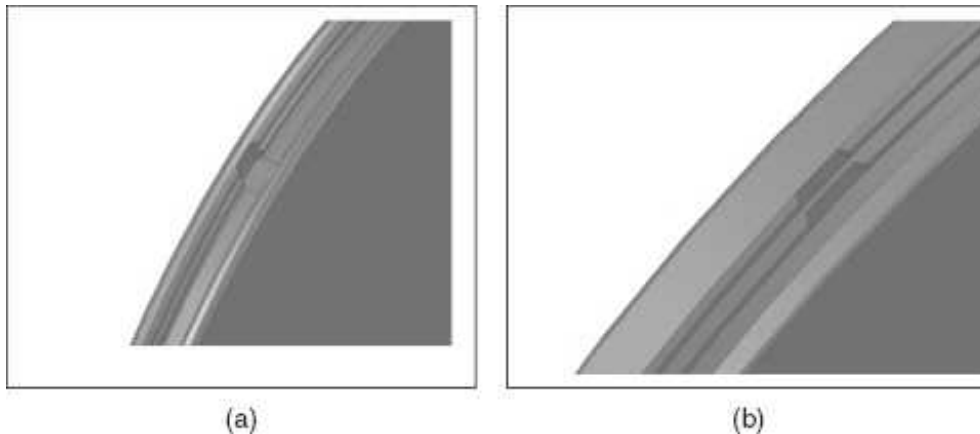
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3.7. Bladed Disk Assembly Processes

No matter how sophisticated the analysis and design of the individual components, and no matter how accurate and precise the manufacture of these components, in the end the processes, techniques, and inspection used in the final assembly of the bladed disk are critical to the successful and reliable operation of the turbine rotor. In this section, we are going to review some of the common processes used in the assembly of the bladed disks. Among these are the installation of the blades in or on the disk to produce the bladed disk assembly. Also covered is the installation of shrouds and auxiliary dampers, with particular emphasis on the installation and assembly of riveted shrouds, i.e., shrouds assembled using pins tends to hold the shroud in place. As these techniques are discussed, the most common forms of in-process inspection and typical acceptance criteria for acceptable assemblies will be reviewed. The processes to be covered are widely used and are common to most makes and models of industrial steam turbines and process drives.

3.7.1. Assembly of Bladed Disks with Circumferential Dovetail Roots

As noted previously, circumferential dovetail roots are by far the most common type in use in present-day process drive steam turbines, making it important for turbine design engineers and reliability engineers alike to understand their assembly processes and their unique assembly requirements to produce a reliable turbine rotor. Dovetail roots are very simple features that involve contact between interlocking shapes on the blade root and the wheel groove. There are two main forms of dovetail roots previously discussed, the internal dovetail form with the wheel hooks on the inside of the wheel groove and the external or straddle root form where the wheel hooks are formed on the exposed lateral sides of the wheel. To install the blades in or on the wheel, there must be a discontinuity in the wheel grooves that allows installation of the blades. This discontinuity is commonly called the *filling slot*, which takes the form of a gap in the wheel grooves through which the blades are installed. Figures 3.30a and 3.30b illustrate the most common forms of filling slots for internal dovetails and external straddle roots, respectively. The assembler simply inserts the blades at the filling slot and then moves the blades around the wheel until the entire complement of blades has been installed.



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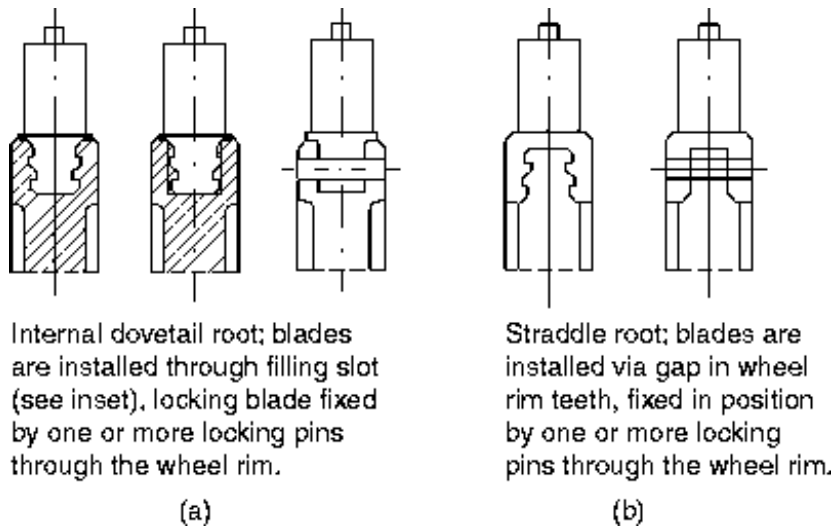
Figure 3.30. Filling slot and filling gaps illustrated.

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3.7.1.1. ASSEMBLY OF DOVETAIL ROOTS

Turbine blades with dovetail roots are installed in the wheel through a hole or a gap in the circular root form of the disk. For the internal dovetail configuration of Fig. 3.31a, the blades are installed via a filling slot, i.e., an opening milled into the wheel's root form that permits the blades to be inserted radially through the slot, then moved circumferentially around the wheel until the entire complement of blades has been installed. The filling slot must then be filled either with a special blade, usually referred to as a locking bucket, or with a blank spacer

piece, which is retained by one or more pins through the wheel rim and the locking bucket root blank. A similar installation for straddle roots is shown in [Fig. 3.31b](#), where the blades are installed through a gap in the circular teeth on the disk. This gap is then closed using a locking bucket that, like that for an internal root form, is retained by one or more pins through the root of the blade and the wheel rim.



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Figure 3.31. Filling slot and locking pins.

Even though the wheel has been designed for a specified integer number of blades, the tolerance stack up for a large number of blades, perhaps 100 or more in many wheels, rarely results in a bladed disk that closes exactly as designed. Most assembly specifications for wheel assembly call for the locking bucket to exhibit a slight circumferential interference with the adjacent blades when it is inserted in the filling slot. This interference tends to force the blades radially outward against the root locks. This effect reduces uncertainty and potential errors in the rotor balancing process due to loose blades. It also tends to create a stiffer blade support during the tenon peening process, where riveted shroud bands are used.

The assembler is shooting for an assembly that is "tight but not too tight." The tightness of the fit at the root of the blade may have a significant influence on the vibratory behavior of individual blades and the final bladed disk assembly. Turbine design engineers recognize the design advantage of the friction damping that results when adjacent blade roots move relative to one another. A final assembly with either too much or too little contact force between adjacent roots may not provide the desired dynamic behavior.

To achieve appropriate tightness or interference when the locking bucket is installed, several options are available. The simplest method utilizes shims cut in the shape of the bucket root form. During assembly of the wheel, the assembler checks the fit and inserts shims between as many blades as necessary to achieve the specified fit. Typically only one shim per blade is used, and it is desirable to space the shims periodically around the wheel to avoid concentrating shims in the last few blades. The assembler must measure and plan ahead, or measure for the last blade or blades, then remove sufficient blades and reinsert with shims to close the wheel. When closing the wheel using shims, it is important that the shims be spaced around the wheel and not concentrated in one space close to locking bucket, to minimize the possibility of introducing excessive unbalance in the final assembly.

Another method to ensure proper closure of the wheel involves the use of the blades that are deliberately produced either slightly oversized or slightly undersized, known, respectively as overs and unders, that are used in combination with standard-size blades to ensure that the wheel closes with the current number of blades. When using this method, the assembler installs a complete set of standard blades and measures the space remaining for the locking bucket. From this information, the number of oversize or undersize blades can be calculated. Next either the entire set or a significant portion of the set is removed from the wheel, then reinstalled with the appropriate number of overs or unders interspersed around the wheel.

An alternate method which is sometimes used is called *mill to close*. In this method the standard blades are made deliberately a slight amount oversize. Then based on the measurement of the space left for the locking bucket, some of or all the blades are milled to remove a small amount of material, ensuring that the row of blades closes correctly.

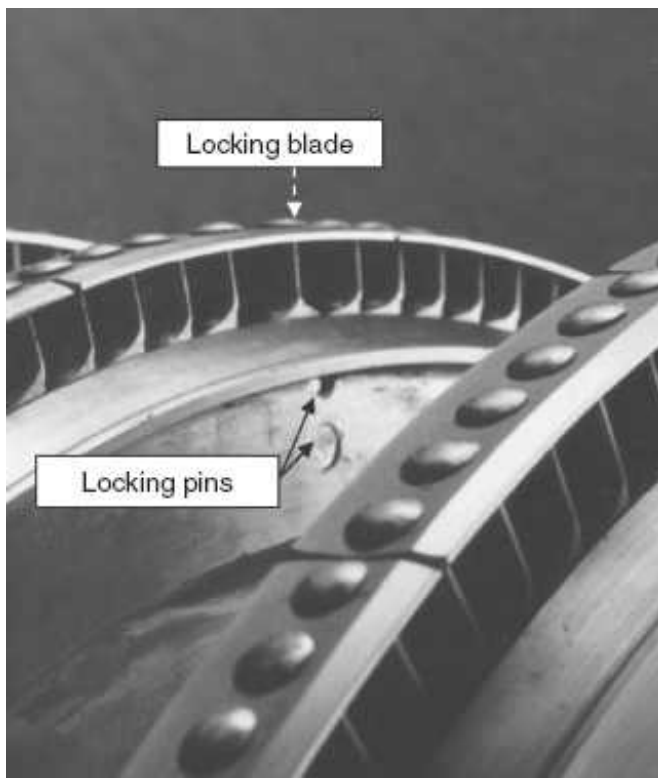
It sometimes happens, especially in bladed disks with a large number of small blades, that the row appears to close correctly with either one more or one fewer blade than is specified by the designer. If a review of the modal behavior of the bladed disk indicates that there is no significant impact on the vibratory behavior of the blades and disk, it is often preferable to accept the small discrepancy in the number of blades rather than use an excessive number of shims or oversize or undersize blades. However, the decision to accept a bladed disk assembly with a discrepancy in the number of blades can only be made after a thorough engineering review of the effects on the modal behavior of the bladed disk assembly.

3.7.1.2. BLADE ROW CLOSURES FOR CIRCUMFERENTIAL DOVETAIL ROOTS

For internal roots, a locking bucket or locking piece is installed in the filling slot in the wheel groove through which the blades are inserted. The locking piece must nearly fill the slot, with close contact on the sides of the groove. Since the locking piece is held in place with one or more hardened steel pins, reamed and installed after the locker is in place, any gap that will result in unsupported pin length is undesirable.

For external or straddle roots, the locking bucket or locking piece fills the gap in the wheel locks that permits installation of the blades. Like the locking bucket for internal roots, the locking bucket or locking piece must have close contact with the sides of the wheel to avoid any unsupported length of the pins.

The design and installation of the locking blades and retaining pins are critical to a successful circumferential root design. Unlike a standard blade with circumferential roots, where the load is carried by a relatively large contact patch and the load is shared by all the teeth in bending, the locking bucket is retained by only one or two pins whose diameter is only a fraction of the width of the root. The pins themselves are highly loaded in shear, and so must be produced from a very strong material, such as tool steel. The fit of the pin in its bore is also important. A tight fit or even a slight interference fit is desirable, as it minimizes bending deflection in the pins and helps to ensure the pins are loaded mainly in shear, with minimal bending stresses. [Figure 3.32](#) illustrates a typical locking pin installation for a blade row with internal dovetail roots.



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Figure 3.32. Locking pins. (Photograph courtesy of Dresser-Rand Company.)

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3.7.2. Bladed Disk Assembly—Axial Fir Tree Roots

As noted before, axial fir tree roots are most commonly used on high-speed and highly loaded turbine stages. The assembly process for axial fir tree roots is very straightforward, requiring little or none of the measurements and adjustments that are required to ensure proper closure of the stage with circumferential dovetail roots. However, there are still some precautions and required practices to ensure the best results in the bladed disk assembly. It is common practice, especially for larger blades, to measure and record the mass weight or the moment weight of each blade, from which installation sequence or order can be calculated to minimize the residual unbalance to variations in blade mass. By their nature axial fir tree roots are easily installed and removed from the wheel, making it easy to exchange the positions of a few blades to fine-tune the residual unbalance of the stage.

When axial roots are used, any interlocking shrouds, such as Z-locks or center-milled integral shrouds, require the simultaneous insertion of all the blades in the stage. When Z-lock shrouds that are designed with significant preload between blades are installed, considerable force may be required to overcome friction between the blades and grooves. A dead blow hammer is often used to work each blade in by a small amount, working around the wheel multiple times until

the blades are all in their desired axial engagement. Axial roots require some positive means to retain the blades in the correct axial location. Many axial roots are retained by the use of pins or bolts installed at the bottom of the wheel slot, as shown in [Fig. 3.33](#), with washers on each end that overlap the wheel face and ends of the roots to prevent axial movement. An alternate design, shown in [Fig. 3.34](#), uses bend-up tabs instead of washers. A sheet metal retainer with a dog bone shape is placed in the bottom of the wheel slot, with a larger tab on either side of the wheel. After the blade is installed above the retainer, the tabs are bent up to overlap the wheel face and end of the blade root, preventing axial movement of the blades relative to the wheel.



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Figure 3.33. Axial roots retained with washers and rivets. (Photograph courtesy of Dresser-Rand Company.)



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Figure 3.34. Axial roots with "dog bone" or bent-tab type of retainers. (Photograph courtesy of Dresser-Rand Company.)

3.7.3. Bladed Disk Assembly—Pinned Roots

Because the root forms do not automatically determine the blade location, the assembly process must correctly locate each blade in relation to the turbine rotor at the correct radius to the turbine centerline and with the airfoil stacking axis in the correct angular relation, not only to the rotor but also to adjacent blades in the stage.

Depending on the tools available and the preference of the process engineer, blades and wheel rim may have pilot holes predrilled, or the drilling may all be done in its entirety after the blade is fixtured in its correct location in the wheel. In either case, the final holes are align-reamed through both blade and wheel rim simultaneously at very close tolerances, ensuring proper fit of the pins. To ensure close fit, in some cases the pins may be ground to match the size of individual bores. In many cases, pins that are sized for a slight interference fit must be cooled to facilitate assembly after align-reaming. After align-reaming, the disk, blades, and pins become, in effect, a matched assembly. In this case, if they are removed for any reason, the blades and pins must be reassembled in their original locations on the disk.

Pins must also be positively retained in their bores. Thermal transients during start-up or large load changes may result in looseness even in interference-fit assemblies. Coupled with vibration and pressure loads on the face of the wheels, pins will "walk" out of their engagement in the bladed wheel rim if they are not positively retained. A common means to retain the pins involves staking or upsetting the material adjacent to the end of the pins in several locations at each end to prevent axial movement in the wheel, but they may also be retained by mechanical fastenings of one sort or another. [Figure 3.35](#) illustrates a typical staked pin and root assembly.

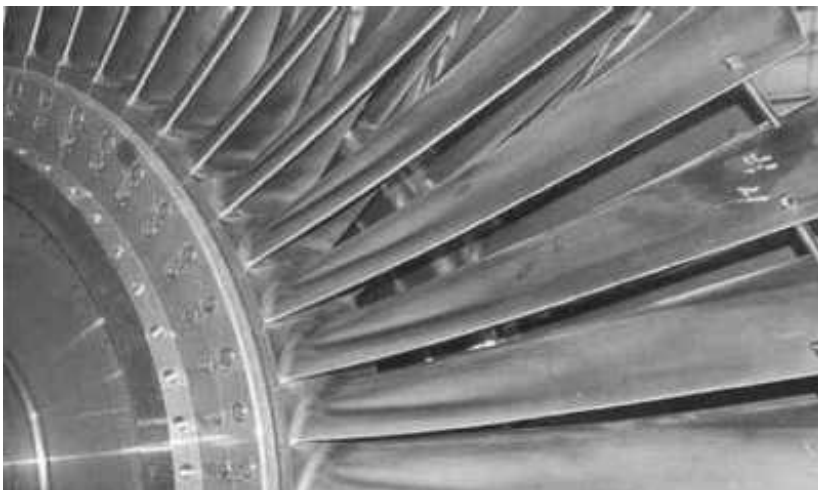


Figure 3.35. Pinned root installation. (Photograph courtesy of Dresser-Rand Company.)

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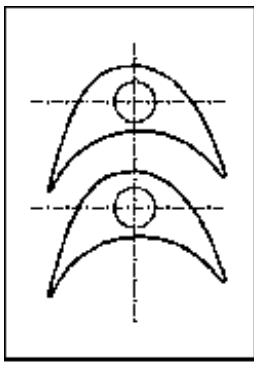
3.7.4. Riveted Shroud Installation

One of the most common shroud configurations is the riveted shroud. In this configuration, a segmented shroud band is attached to the blades by tenons that extend through holes in the shroud and that are then peened to deform and expand the tenon to permanently attach the shroud to the blade tips. Correct assembly of the shroud band segments and peening of the tenons are critical to long-term reliability. The most critical process is peening the tenon, to deform it into the classic rivet shape. While the riveting process can be automated to some extent, it still often depends on operator skill for acceptable results. For some cases, such as kidney-shaped tenons, assembly involves manual operations, where good results depend entirely on the craftsmanship and skill of the operator.

Stage designers often use the shroud to create a specific blade packeting plan to control the modal and vibratory behavior of the bladed disk. Shroud segments are specified by the turbine design engineer to group a specific number of blades into a specific number of packets. During assembly, it is therefore important to ensure that the correct number of blades is installed through the use of shims or over- and undersized buckets.

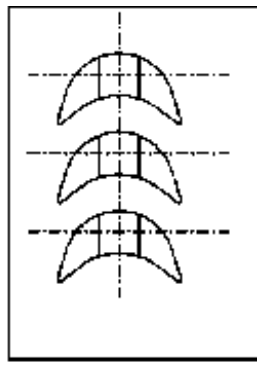
The use of very long shroud segments can create difficulty in assembling the shroud to the blades. Due to the slight angular displacement between adjacent blades, the holes in the shroud must be slightly oversize to permit installation over the tenons. Very long segments exacerbate this problem. When long or continuous shroud bands are specified, a common solution is to utilize a layered shroud structure. This may involve a ship-lap feature at adjacent segments, or it may involve a double-layer shroud, such as where six-blade shroud segments are overlapped by three blades at each end to create an effective double-layer continuous shroud band.

As one might imagine, the design of the tenon has a major influence on the cost and on the difficulty of assembling and peening a riveted shroud assembly. The most common type of tenon is a simple round shape extending from the tip of the airfoil. Round tenons are the easiest to produce and install. [Figure 3.36a](#) shows the blade with a round tenon. Shroud band segments can be produced with either punched, drilled, or milled holes.



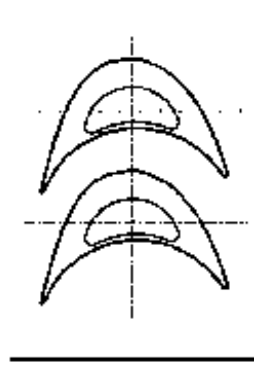
(a) Round tenon

- Most common form
- Turned or milled in separate operation
- Simple to install



(b) Sectional tenon

- Most easily machined
- Inexpensive
- Requires punched holes in shroud band
- Low stress applications



(c) "Kidney" tenon

- Most costly
- Large, "beefy" airfoil sections
- Heavy shroud band
- Difficult peening process
- Usually manually peened

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Figure 3.36. Tenons for riveted shrouds can be round, sectional, or square "kidney" shapes.

The least expensive tenons to produce during blade production are the so-called sectional tenons, as illustrated in [Fig. 3.36b](#). Sectional tenons are square or rectangular and are very inexpensively formed by a simple milling operation during blade manufacture. While the tenons themselves are less expensive to produce, the matching holes in the shroud band must be produced by a punching process, which tends to limit its use to relatively thin shroud band material that can be easily punched. The rectangular tenon shape is evident in [Fig. 3.37](#), showing a shroud with sectional tenons.



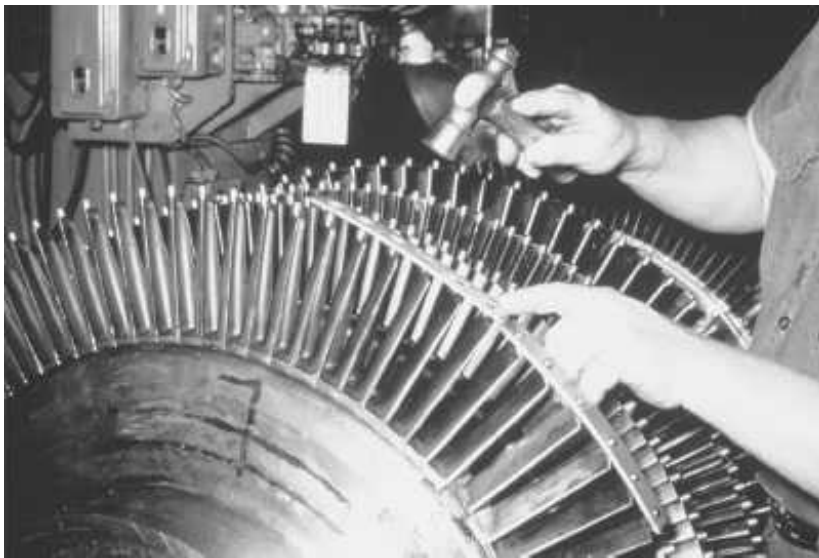
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Figure 3.37. Sectional tenons after peening. Note the rectangular shape of the finished tenons. (Photograph courtesy of Dresser-Rand Company.)

Kidney-shaped tenons, named for their shape and shown in [Fig. 3.36c](#), are sometimes used when thick shroud band material must be attached to blades with large, robust airfoil sections. Since they can only be produced by a milling process, kidney-shaped tenons are the most expensive to produce and create the

most difficulties during the peening process. In the past, kidney-shaped rivets were peened using manual processes. In most cases, this meant the assembler used a pneumatic hammer to expand and shape the end of the tenon into the desired rivet head shape. This process depended in large part on the craftsmanship and skill of the assembler. However, orbital riveting machines are now available that can be programmed to peen kidney-shaped rivets, resulting in more consistent results.

Shroud band segments must be properly prepared for installation, which is illustrated by [Fig. 3.38](#). For very stiff blades, it is often necessary to mark the hole locations from the blades after installation. In this way, variations due to shims or oversize and undersize blades can be accounted for. On the other hand, if the blades are very flexible, such as drawn blades, the shroud may be drilled or punched based on the theoretical or design locations of the blades to ensure they are properly oriented in the wheel.



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Figure 3.38. Installing shroud segments prior to peening. (Photograph courtesy of Dresser-Rand Company.)

Shroud bands for sectional rivets are usually punched with a square or rectangular shape to match the tenon shape. Holes for round tenons may be either drilled or punched, depending on hole size and material thickness. In special cases, the holes may be produced by milling to minimize deformation of the segments or to achieve close hole diameter control. Kidney-shaped rivets require the use of shroud segments with holes that are either punched using specially shaped tools or milled to size and shape on a CNC milling center—both expensive processes.

In riveted shrouds, the critical operation is the process of upsetting and forming the tenon into the final "rivet" shape. Peening the tenons involves deliberate

plastic deformation of the tenon, making it easy to understand the importance of high ductility in the blade material. Low ductility in the blade material may create serious problems during the peening process, including cracks and even fractures in the tenon.

In some cases, the tenon may be locally heated immediately prior to upsetting. To be effective, the material must be heated to a sufficient temperature to reduce the material's ultimate strength. Heating may be used for tenons with large cross-sectional area to reduce the total force and energy imparted to the blade. It may also be used to allow peened tenons to be used with materials having higher strength or lower ductility that would otherwise rule out the use of peened tenons. For example, riveted shrouds have been installed on titanium blades by heating the tenons prior to upsetting. While heating the tenons can be very effective, it must be approached with great caution. If the heating process is not carefully controlled, there is a danger that the blade or shroud material may attain high enough temperature to change its material properties.

The peening process can be carried out using one of several related processes, illustrated conceptually by [Fig. 3.39](#). One common procedure uses an automatic hammer, like that shown by [Fig. 3.40](#), with its anvil shaped to produce the desired rivet shape. The hammer strikes the tenon up to 200 times per minute, while simultaneously rotating at about 15 rpm, with the speed controlled by the operator.

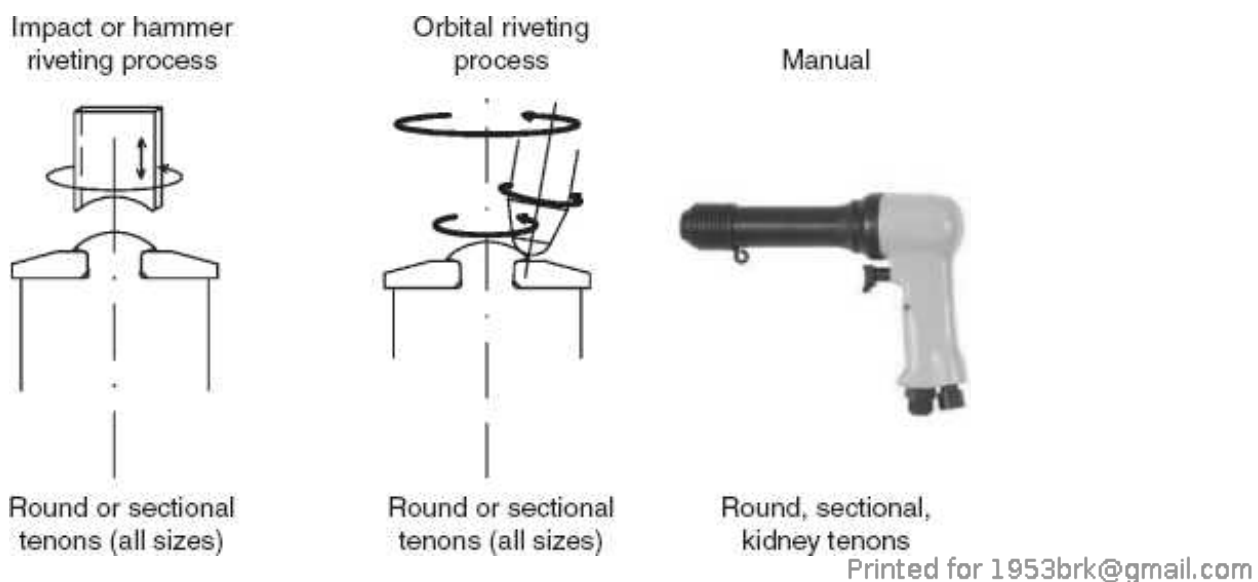
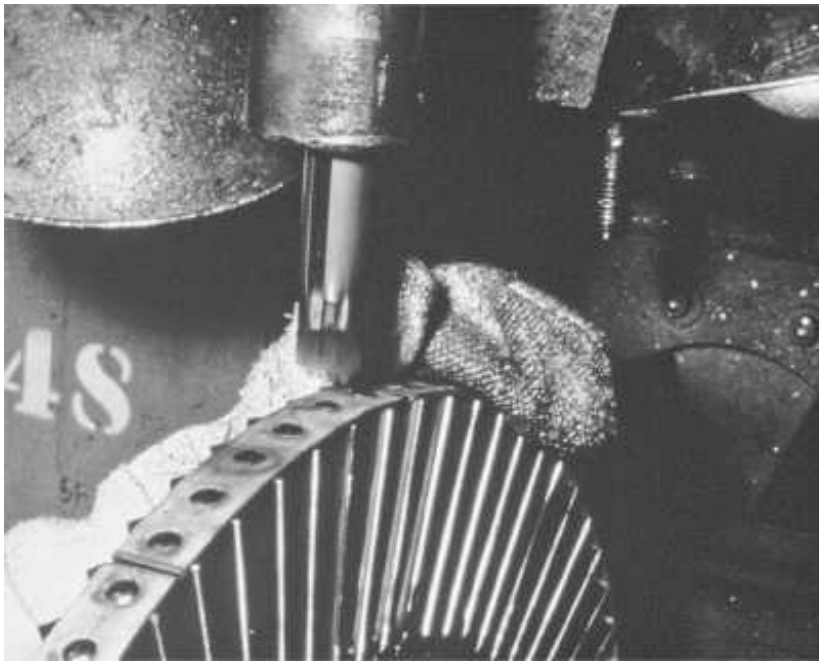


Figure 3.39. Peening processes.



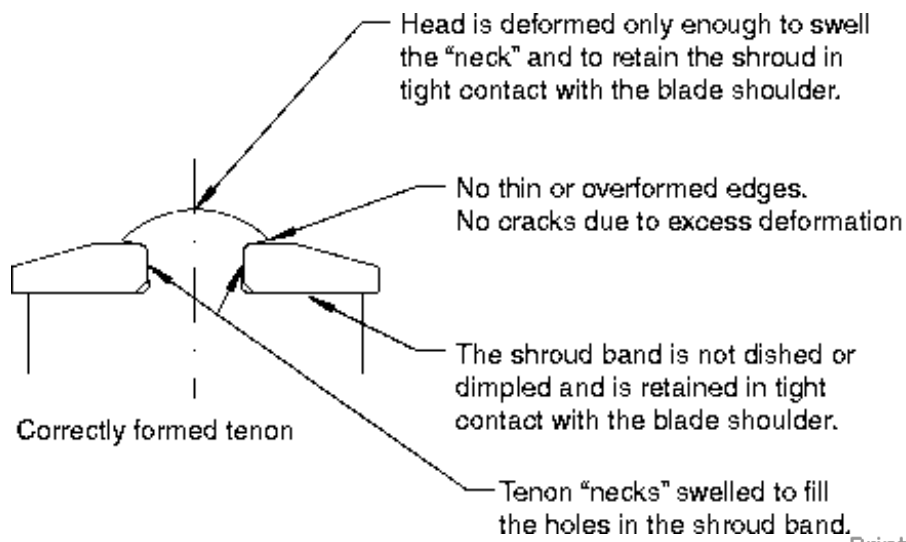
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Figure 3.40. Automatic hammer-type riveting machine. (Photograph courtesy of Dresser-Rand Company.)

The orbital riveting process is more automated, with an orbital head forcing a hardened head against the tenon. The anvil rotates about its own axis, while the head simultaneously nutates the anvil's axis about the tenon's centerline. The anvil's axis is usually held at a slight angle relative to the tenon's axis.

For irregularly shaped rivets, such as Kidney-shaped tenons, the only option may be manual peening using an air-operated impact hammer. This process may, of course, be used on any tenon if automated equipment is not available. With the manual peening process, the results are almost entirely dependent on the skill, experience, and craftsmanship of the operator.

Figure 3.41 illustrates the characteristics of a well-executed peened tenon. Figure 3.42 is a photograph of an example of correctly formed tenons. The tenons in a riveted shroud cannot be easily inspected after assembly, so how do we ensure good-quality rivets?



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Figure 3.41. Cross section of correctly upset and formed tenon.

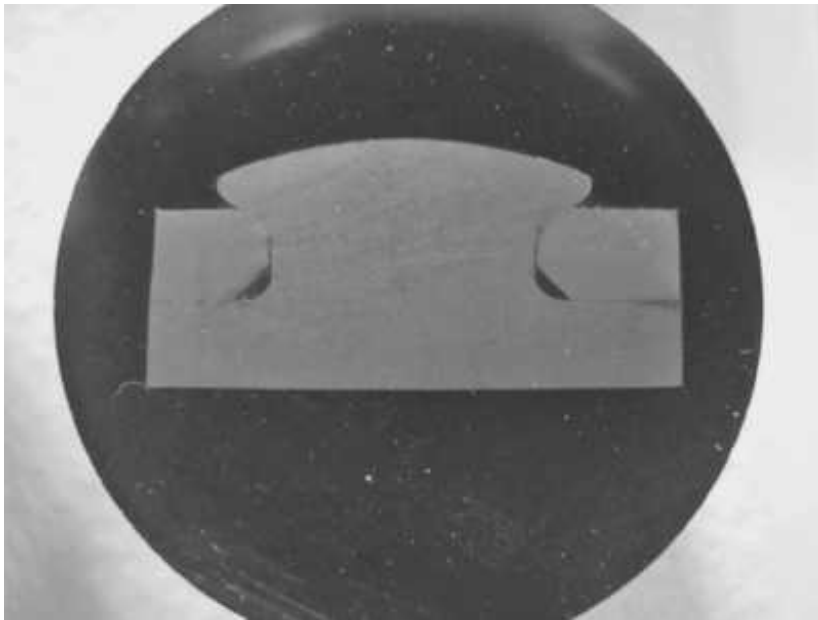


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Figure 3.42. Example of correctly formed tenons. (Photograph courtesy of Dresser-Rand Company.)

As with any process that is not easily checked or inspected after completion, the only practical approach is to develop a detailed process specification, controlling as many of the critical process variables as possible. In addition to machine parameters such as hammer size and speed, process development must include qualification tests of both the process and the operators. Most power hammers are at least partly dependent on the skill and experience of the operator. For manual peening with an air hammer, operator qualification is the single most critical step in the overall process qualification and documentation. Process and operator qualification testing relies on the production of sample riveted tenons on sample blades in either the production disk or a test dummy disk. The blades and shroud bands are assembled using the same process as the production disk. The sample blades are then removed, and the tenons are sectioned so that important

parameters such as neck filling, head shape, and tight contact between the shroud band and the shoulders of the blade tip can be checked. Figure 3.43 is a photograph of a qualification sample that illustrates all the attributes required for an acceptable peened tenon. In most cases, the OEM or service shop will perform qualification tests on a regular periodic basis, usually quarterly or semiannually, and will retain the results of the process and personnel qualifications in its records. For critical stages or units, or for unusual designs, it may be advisable to carry out qualification tests on the specific design being used to ensure results meet the acceptance criteria. Although the assembled shroud cannot be completely inspected, there are still some common external checks that can be carried out, including subjecting the peened tenons to a dye penetrant inspection process or, in limited cases, ultrasonic inspection to check for cracks in the heads.



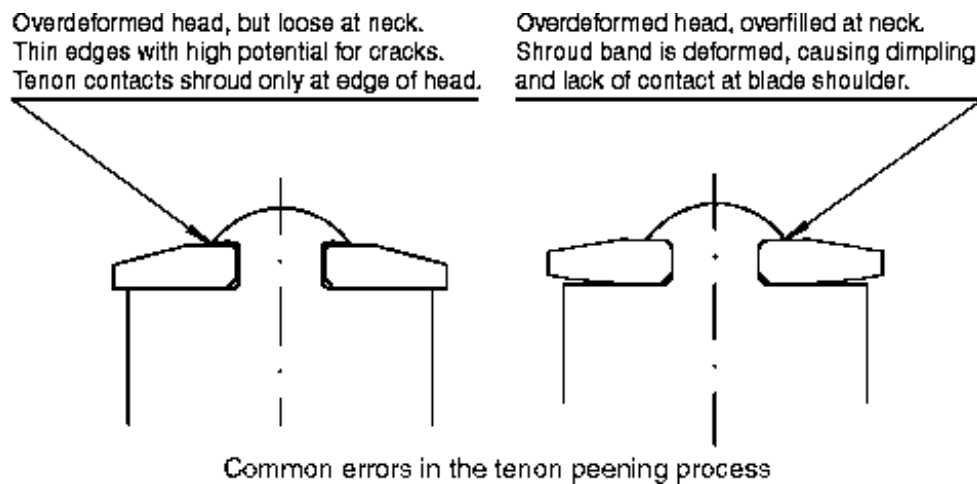
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Figure 3.43. Qualification sample for peened tenon illustrating correctly formed head, good contact at neck, and negligible distortion in shroud band. (Photograph courtesy of Dresser-Rand Company.)

Although it is difficult to inspect the finished tenons after the peening process is completed, some common problems that can affect reliability are easily identified by looking for their telltale signs.

A common error in manual processes results in a simple mushrooming of the edges of the tenon, without sufficiently upsetting the neck of the tenon to fill the hole in the shroud band, seen in Fig. 3.44. The edges of the head often are overstretched, resulting in paper-thin edges and possible cracking. With insufficient metal in contact to resist centrifugal loads on the shroud, the shroud

becomes loose, losing contact with the blade shoulder. Loose holes and insufficient contact with the blade shoulder reduce the effectiveness of the shroud as both damper and structural stiffener.



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Figure 3.44. Common riveted shroud errors.

An equally common error is overdriving the rivet. The head is "pounded down" until it starts to embed in the shroud band surface, and the tenon's neck is swelled until it completely fills the holes and may ultimately expand the hole in the shroud beyond yield. The shroud band may exhibit dishing or dimpling around the tenon and may lift away from the shoulder of the blade, as [Fig. 3.44](#) shows.

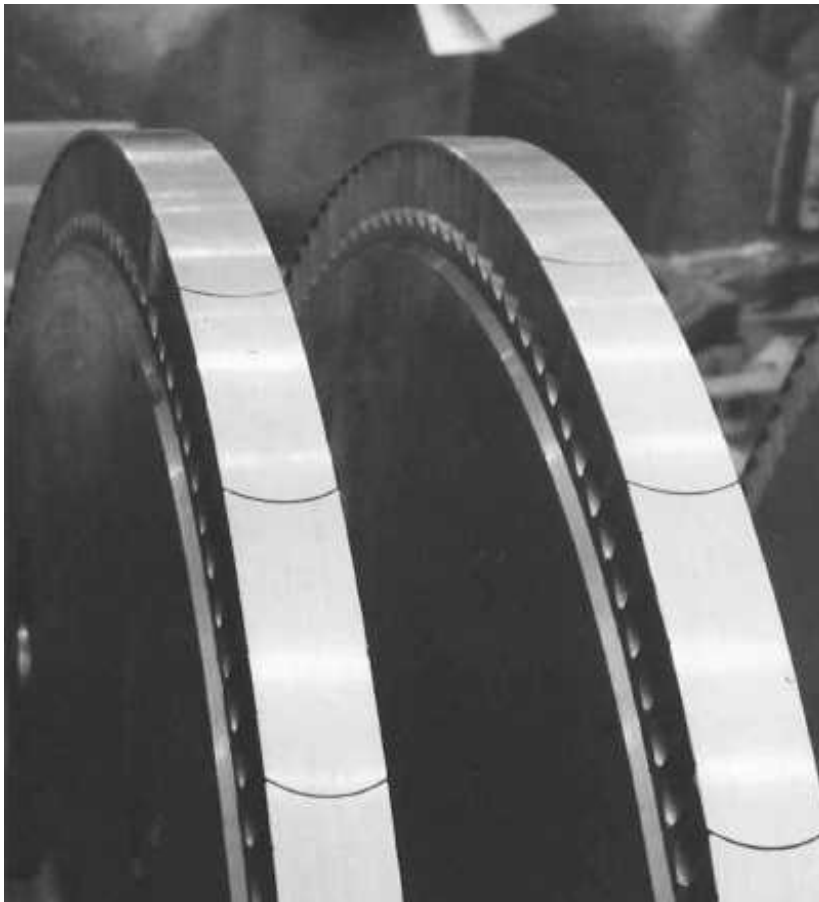
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3.7.5. Integral Shroud Installation

Since integral shrouds are an integral part of the blades themselves, it may seem strange to discuss the installation of integral shrouds. While integral shrouds are by definition installed with the blades, the installation of blades with integral shrouds may require some special considerations. Most integral shrouds are produced with either rectangular or center-milled nesting. Depending on the stage requirements, they may be installed with small blade-to-blade gaps, or in tight contact with adjacent shrouds. As pointed out above, when axial fir tree roots are used with interlocking shrouds such as Z-lock shrouds or integral shrouds made to match a curved platform shape, it necessitates the simultaneous installation of the complete complement of blades in each row.

In most stages with integral shrouds, it is difficult to ensure positive contact between adjacent shrouds once the disk is operating at speed, so designers always attempt to design blades and bladed disk assemblies that can operate reliably either with or without such positive contact between adjacent integral shrouds. Complications arise when the stage designer must ensure structural

stiffening and damping from the shrouds in the stage with simple integral shroud shapes. The problem is especially difficult when it comes to capturing the benefits of blade packeting in a stage with integral shrouds. One commonly used approach to this problem is shown in [Fig. 3.45](#). The blades in this stage are produced with shrouds designed to be in contact with adjacent shrouds when installed in the wheel. The packets, six blades each in this case, are produced by inserting a shim after every six blades. In the assembly of this wheel, shims are only used in the locations that support the packeting scheme, and at these selected shim locations the shim thicknesses are adjusted to produce the desired wheel closure.



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Figure 3.45. Packeted integral shrouds. (Photograph courtesy of Dresser-Rand Company.)

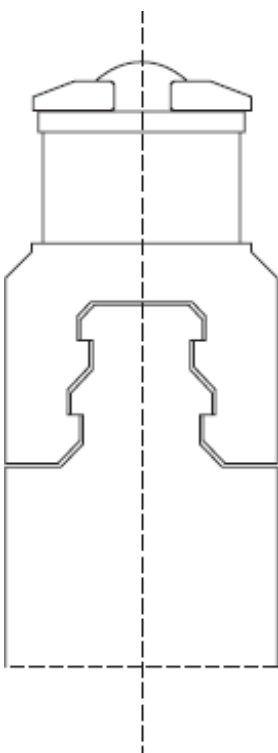
Another method to ensure structural coupling between integral shrouds involves the insertion of damping wires or "friction" bands, an example of which is shown in [Fig. 3.46](#). Previously, [Fig. 3.22](#) showed two common types of inserted wires and bands used to ensure structure coupling between adjacent shrouds. Depending on the way the wire or band is retained, they may impart significant friction damping as well. A special variant includes "double-covered" blades, which are machined with tenons atop integral shrouds ([Fig. 3.47](#)). After the blades are installed, a conventional riveted shroud band is installed, retained by peening the

tenons, resulting in a very robust bladed disk assembly. Double-covered blades are expensive to produce, so they are typically only used in very highly loaded stages, such as the control stages in high-speed process drives and in some critical marine turbine applications.



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Figure 3.46. Photo of friction band shroud wire installed. (Photograph courtesy of Dresser-Rand Company.)



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Figure 3.47. Double-covered shroud construction—conventional riveted shroud installed atop blades with integral shrouds.

Most integral shrouds are trimmed after installation to eliminate axial runout from the faces of the shroud, and to eliminate radial runout of the OD surfaces of the shroud. To facilitate this operation, blades are produced with extra stock on the integral shrouds just for this final trimming operation.

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3.8. Inspection, Testing, and Quality Assurance

In the preceding discussions, we touched on many of the manufacturing processes as well as some of the critical inspection processes to ensure a reliable bladed disk assembly. However, given the importance of the blades themselves, as well as that of the complete bladed disk assembly, a discussion of the role of inspection, testing, and quality assurance activities associated with the production assembly and operation of steam turbine blades is warranted.

Many engineers mistakenly believe that quality assurance and quality control activities are the sole province of the inspectors and quality assurance department. There are very good reasons, however, that turbine design engineers and reliability engineers must be involved in the development and execution of a comprehensive quality plan that addresses all the critical manufacturing and assembly processes associated with the production of steam turbine blades and bladed disk assemblies. At the design stage, and especially during the design of individual components, virtually all the important design parameters (material properties, part dimensions, and assembly tolerances, among others) are only assumptions or specifications on the part of the designer. As the reader will learn in subsequent chapters, the calculated blade frequencies, blade loading limits, and overspeed limits are all sensitive to the final, as-built values of these parameters. To ensure that the final product performs in accordance with the designer's predictions, the actual values of key design parameters must meet or exceed the designer's assumed values. The vehicle that is used to make sure this occurs is the *Quality Plan*, also known as the *Inspection and Test Plan* or *ITP*.

The inspection and test plan has three major objectives. The first is to ensure that the minimum requirements for each component, as defined by the turbine design engineer, are met. It is also the vehicle to ensure that any additional or special requirements stemming from contract or customer specifications are defined and carried out during execution of component manufacture. And finally it provides a

record of the actual production and assembly of the components and assemblies covered by the plan. If necessary, these records can be used in the future to diagnose and troubleshoot problems, and they form the basis for improved processes and results on future projects. A good-quality plan lays out an objective set of processes and acceptance criteria for the project, leaving as little as possible to later subjective decisions by manufacturing personnel, inspectors, and customer representatives. As a minimum, the inspection and test plan must detail the characteristics to be controlled, any controlling documents and standards that pertain to these characteristics, the acceptance criteria for these characteristics, the methods by which these characteristics are to be measured and documented, record-keeping requirements, and finally a list of any inspection points requiring observation by a customer representative.

Although the standard was specifically written to address repairs of existing rotating machinery, API Standard 687 contains some excellent examples of ITPs for a variety of turbomachinery rotor repairs, including steam turbines, which are covered by Section 4 in the standard. The proforma quality plans in this document provide an excellent reference for turbine design engineers, reliability specialists, inspectors, and end users. The inspection activities and documentation requirements are, of course, applicable to brand new steam turbines as well as repair and reblading activities for existing turbine rotors.

Citation

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