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IMPELLER MANUFACTURING – UNDERSTANDING THE METHODS & THEIR IMPACT ON PERFORMANCE

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Jim is a member of ASME and the ASME Turbomachinery Committee. He has authored or co-authored more than 60 technical publications and has instructed seminars and tutorials at Texas A&M and Dresser-Rand. He currently holds several U.S. patents. Jim was elected an ASME Fellow in 2008 and was also selected as a Dresser-Rand Engineering Fellow in 2015. He was given a Lifetime Achievement award by Hydrocarbon Processing magazine in 2019.

ABSTRACT

This tutorial provides an overview of the manufacturing processes used to build centrifugal compressor impellers and how the various processes can impact the performance of these critically important components. Comments are offered on how client demand for higher performance drove OEMs to more advanced manufacturing methods. A brief overview is also provided on the dimensions and features that are critical to achieving the expected impeller performance. Finally, the tutorial provides a detailed discussion on the various techniques being used to fabricate impellers today and offers some insights into possible methods that will be used in the future.

INTRODUCTION

Impellers have been called the heart of centrifugal compressor stages because of their critical role in the performance of such machines. If the impellers do not perform as expected (i.e., achieve the predicted efficiency, head coefficient and range), the overall performance of the compressor cannot meet expectations and no amount of changes to the associated stationary components will correct this situation. The impellers must perform as predicted, and to perform as predicted, the impeller geometries must be accurate: must conform to the design dimensions provided by engineering.

Throughout the years, customer requirements have pushed the design, and subsequently the manufacturing methods, of impellers as discussed by Engeda (1998), Bloch (2006), Sorokes/Kuzdzal (2010), Laney et al (2016), Peng et al (2017) and others. Their works touched on the important role of manufacturing in compressor evolution. This tutorial goes into greater detail and explains the interaction between Customer Requirements, Advancements in On-Site Technology, Advancements in Engineering Tools, Advancements in Impeller Design, and Advancements in Manufacturing Tools as shown in Figure 1. The interaction will be described as cyclical and therefore continually evolving in the industry.

Figure 1 – Manufacturing Development Cycle

The advancements in manufacturing techniques were followed by breakthroughs in joining methods. From a simple riveted impeller to complex electron beam techniques, evolution of joining methods created new ways to construct the finished impeller. With each new technique, quality assurance steps had to be implemented to ensure the finished impeller met the strength, dimensional accuracies, and other aerodynamic requirements. It also must be recognized that the different manufacturing techniques provide varying degrees of dimensional accuracy, mechanical strength, fatigue resistance, etc. This is due to the machining, forming and/or joining methods involved in the construction process. These considerations will be discussed in the sections that follow. However, before proceeding with those topics, it is important that one understands the critical geometric dimensions in an impeller and how deviations from the design dimensions on those critical features will impact the compressor's aerodynamic performance.

"Critical To Quality" Impeller Dimensions

The phrase "Critical To Quality" (CTQ) is often used in quality assurance discussions to refer to those dimensions in a part that are vital to achieving the operating requirements of said part. There are numerous geometric dimensions and features that are important in ensuring that centrifugal impellers perform as predicted both mechanically and aerodynamically. [*Note: For clarity, the term "dimension" is used herein for any geometric parameter than can be specified by a single number. The term "feature" is used herein for any surface or geometric shape that is specified by multiple dimensions.*] However, some dimensions and features are more important than others and are, therefore, labeled CTQ dimensions. The CTQ dimensions for impellers are not necessarily the same throughout the centrifugal compressor world, because they can be impacted by the compressor service, application requirements, etc. Still, there are certain dimensions or features that are universally recognized as key factors or CTQs in establishing the impeller's performance. These are listed below and illustrated in Figure 2 below:

Dimensions:

- Exit diameter, D_2 – inches or mm
- Exit width (or blade height), b_2 – inches or mm
- Blade exit angle at shroud, β_{2S} – degrees
- Blade exit angle at hub, β_{2H} -- degrees
- Blade thickness at exit, Thk2 – inches or mm (not shown in figure)
- Shroud diameter at leading edge, D_{1S} – inches or mm

- Blade leading edge angle at shroud, β_{1S} -- degrees
- Hub diameter at leading edge, D_{1H} – inches or mm
- Blade leading edge angle at hub, β_{1H} – degrees
- Passage height at leading edge, b_1 – inches or mm
- Blade thickness at inlet, Thk1 – inches or mm
- Impeller throat area, Athr – square inches or mm^2 (not shown in the figure)

Features:

- Cover or shroud contour – X,Y, Z or R,Z,θ
- Hub or disk contour – X,Y, Z or R,Z,θ
- Blade shape – X,Y, Z or R,Z,θ
- Aero flow path surface roughness – RMS, RA, etc.

Note: Surface roughness is treated as a feature because there might be different allowable surface roughnesses on different surfaces.

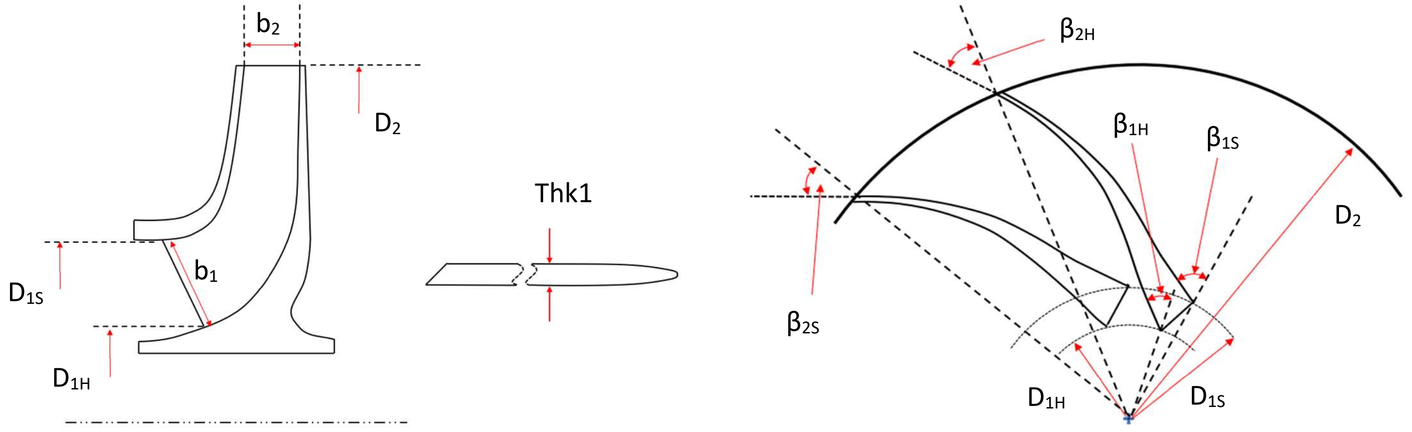


Figure 2 – Impeller geometry nomenclature – *Note: Blade angles in the figure are measured from radial line. Some OEMs measure angles relative to a tangent line.*

Deviations of these CTQ dimensions or features from the design values can cause the impeller to not perform as predicted. If the impellers do not perform as expected, the overall compressor performance will also suffer (Sorokes, 2003). Predictions are almost always based on “as designed” dimensions and/or surfaces. From a high level, for an impeller, the CTQs can be broken down into three regions… the impeller inlet, the impeller exit, and the region between the impeller inlet and exit or “mid-passage” region. Although these regions rigorously are inter-related, each region and their dimensional inaccuracies will be treated separately in the high-level discussions that follow.

The impeller inlet region

The design point capacity of an impeller is the performance parameter most significantly impacted by the impeller inlet geometry. The hub and shroud leading edge diameters (D1H and D1S) along with the passage height at the leading edge (b1) establish the inlet area. The flow through said inlet area along with the rotational speed of the impeller establish the flow angles onto the impeller blading. In turn, the impeller blade angles across the leading edge (β1X) determine how much incidence (or misalignment) there is between the gas flow angles and the impeller blade angles. In general, the impeller best efficiency flow rate occurs most often at the flow rate where minimal incidence occurs across the leading edge. Therefore, if the diameters or blade angles deviate from the design dimensions, there could be a shift in the location of the best efficiency point and the entire stage performance map. If this shift is significant, it could cause the overall machine to miss its required performance targets. An example of a performance map shift is shown in Figure 3.

Another significant consideration at the impeller inlet is the throat area. The throat area sets the maximum capacity or choke limit of the impeller. It is defined as the minimum geometric area through which all of the flow must pass. It is typically determined by generating a 3-D plane that connects the minimum distances between two adjacent blades in a passage (see Figure 4) and then multiplying by the number of passages or blades at the impeller inlet. Note that the leading edge thickness and blade thickness influence

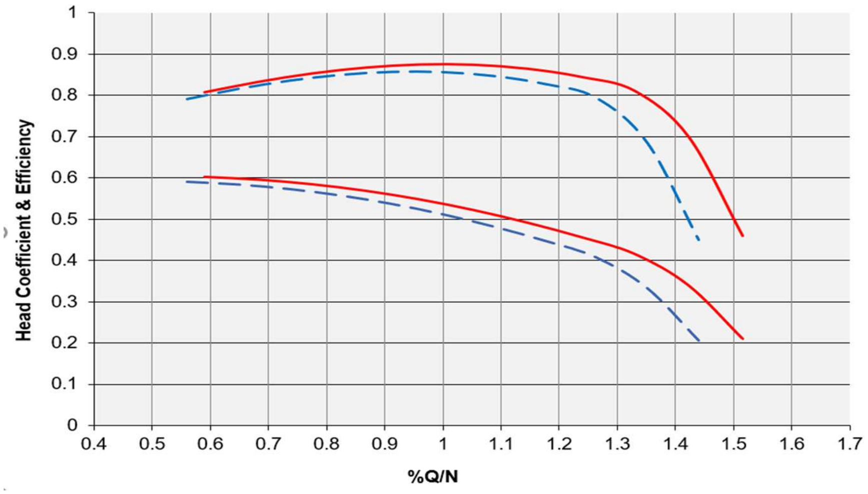


Figure 3 – Stage map – With no deviations in red – With deviations in blue dash

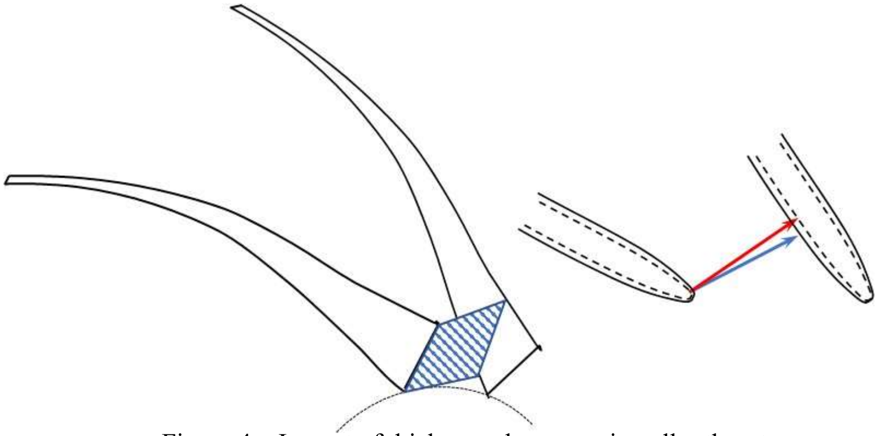


Figure 4 – Impact of thickness change on impeller throat area

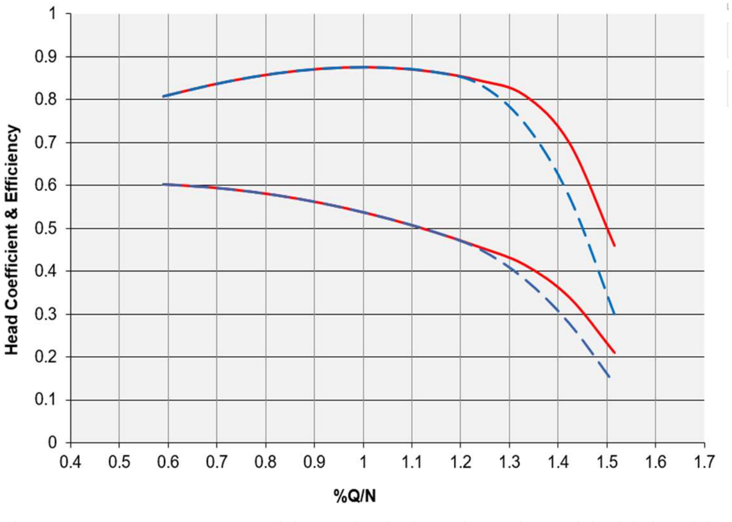


Figure 5 – Stage map – With no deviations in red – With thicker blade in dashed blue

the throat area. Therefore, if the blades are too thick, the throat area decreases, and the overload capacity of the impeller is reduced (see Figure 5). It is also possible for the throat area to increase or decrease due to deformation of the impeller blade in the inlet region.

Secondary factors such as the curvature along the shroud and hub contours as well as the blade shape can also influence the impeller capacity and other factors; such as stall and choke; so, it is important that these features also align well geometrically with the design contours.

The impeller exit region

The impeller exit region is a primary factor in establishing the head level and/or pressure ratio generated by the impeller. A key element in the Euler equation used to determine the head generated by an impeller is the product of the tip speed (U_2) and the impeller exit tangential velocity (C_{U2}). For an impeller with no inlet swirl, the equation can be expressed as follows:

$$\mathrm{Head_P} = \frac{\eta_P}{g_c}(U_2 \cdot C_{U2})$$

Where: ηp = Polytropic efficiency
g_c = Gravitational constant
C_{U2} = Impeller exit tangential velocity
U_2 = Tip speed

The tip speed is a function of the impeller exit diameter and the rotational speed; i.e., $U_2 = N \pi D_2 / 720$ in U.S. customary units. The exit tangential velocity is dependent on a number of dimensions including: the tip speed (U_2), the impeller exit blade angle (β_2), and the impeller exit area. The exit area is, in turn, dependent on the impeller exit diameter (D_2), the impeller exit width or passage height (b_2), and the exit blade thickness (Thk_2) and is a primary factor in determining the impeller exit meridional or radial velocity, C_{M2}. The various velocity components establish the impeller exit velocity triangle as shown in Figure 6. Because the tip speed and the exit tangential velocity are co-linear, the C_{U2} vector was made thicker for clarity. [Note: The influences of slip or deviation and aerodynamic blockage are ignored in the velocity triangles shown herein. This does not detract from the illustrative benefits of these figures.]

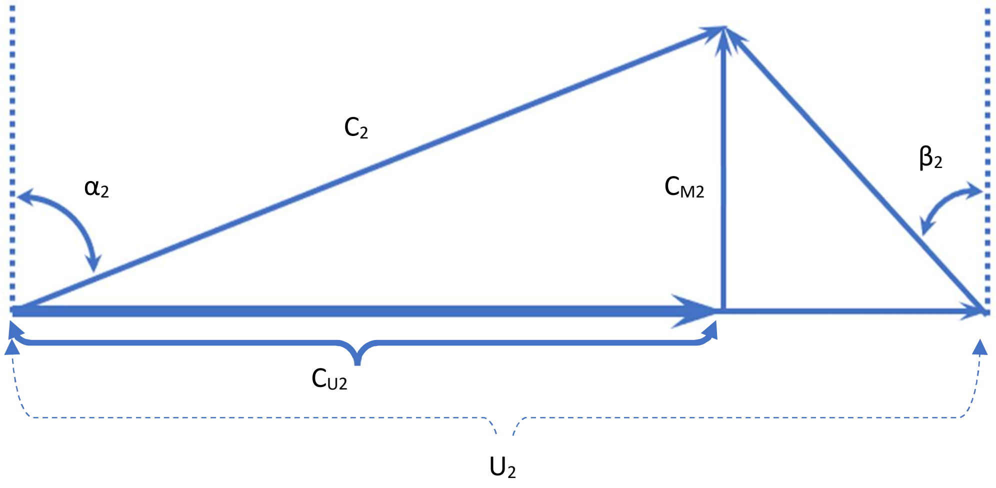


Figure 6 – Impeller exit velocity diagram

As noted, the head level is dependent on the tip speed and exit tangential velocity, which are functions of the geometric parameters as describe above. Therefore, changes in dimension such as the impeller diameter, exit width, exit angle, and blade thickness can directly impact the head or pressure rise generated by the impeller. Changes in these parameters can also impact the impeller exit flow angle, which can be a major consideration for stages with vaned diffusers downstream of the impeller. That is, changes in the impeller exit flow angle will create unexpected incidence on the downstream diffuser vanes, resulting in higher than expected losses and possible loss of flow range.

As illustrations of the impact of geometric deviations, consider the various impeller exit velocity triangles shown in Figure 7. In each case, note the change in length of the exit tangential velocity (C_{U2}) and exit flow angle resulting from the deviation. For reference, the velocity triangle assuming no geometric deviations is shown as solid faded blue lines and the impact of the deviations are shown in red dashed lines. The triangle in Figure 7A shows the impact of an undersized exit width. Excess blade thickness would also result in a triangle similar to Figure 7A because excess blade thickness and a narrow exit width both result in a reduction in exit area. If the impeller was mis-machined or deformed during fabrication such that the backsweep or exit blade angle (relative to a radial line) increased, the result would be Figure 7B. Finally, the impact of an over-sized exit width and an increase in exit blade angle is shown in Figure 7C. In this latter case, note that C_{U2} is the same for the triangles with and without deviation. However, the case with deviations has a different exit flow angle, α_2. This could be problematic if there are vaned diffusers downstream of the impeller with the result being a loss in overload capacity due to higher incidence.

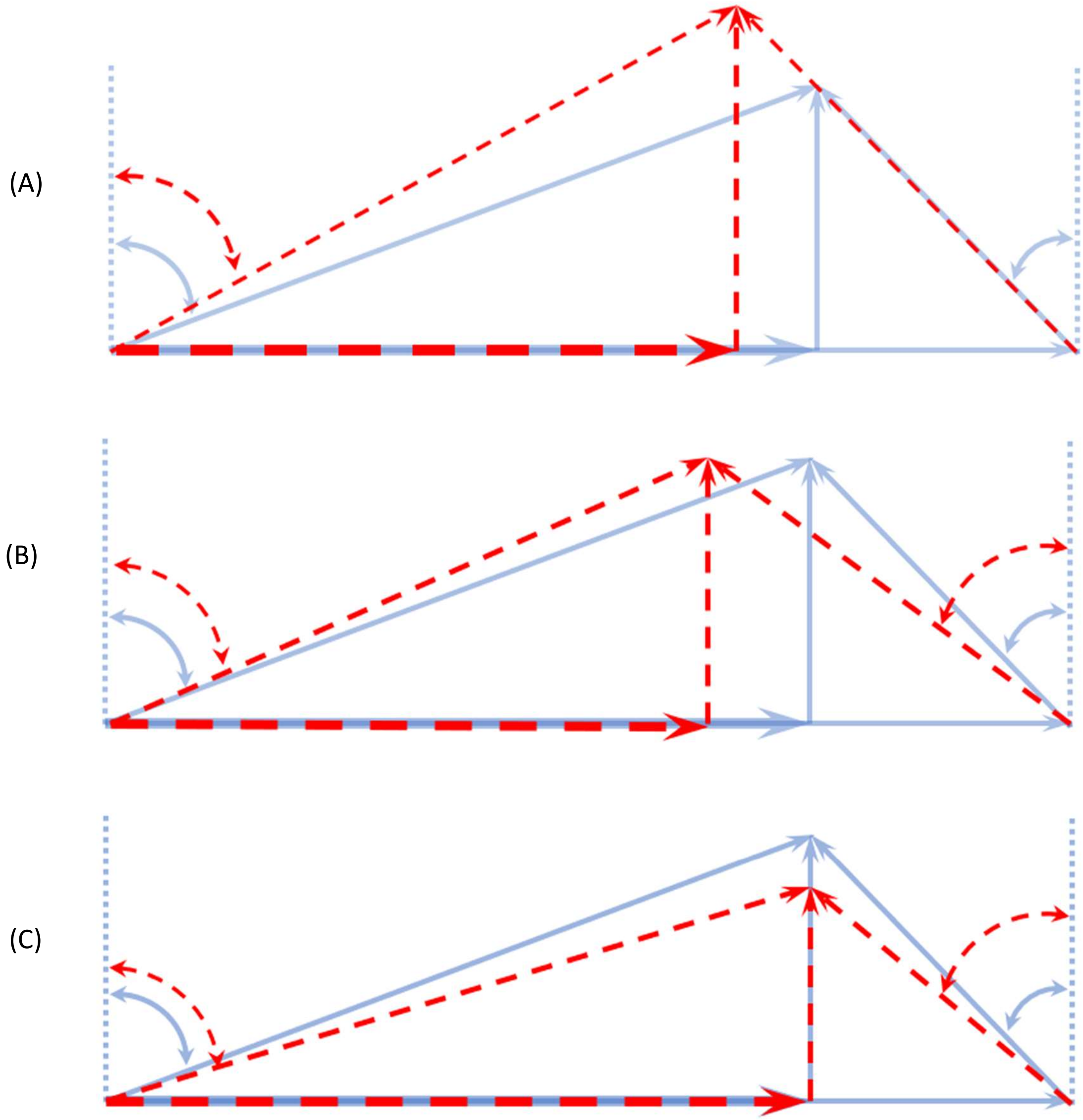


Figure 7 – Impeller exit velocity diagrams – Blue is without deviations – Red is with deviations as described in the text

The mid-passage region

As noted earlier, rigorously, it is not possible to consider the regions of an impeller as independent because the regions must function in unison to achieve peak performance. Some could argue that the mid-passage region is the most important because it connects the other two, but it is also the most difficult to inspect or validate once a part is complete. While most of the geometric parameters addressed to this point can be measured with scales, calipers, micrometers or digital inclinometers, features in the mid-passage region such as the blade profile typically must be assessed using laser or light scanning systems or coordinate measuring machines (CMMs). Examples of laser scan results on a finished impeller are shown in Figure 8. The values shown in the figure are deviations relative to the CAD model. While such scanning is typically not done on day-to-day production impellers, it is quite often done on "first article" components making use of novel manufacturing or joining techniques to validate that the new method meets agreed-upon dimensional tolerances.

The mid-passage region is included primarily to emphasize the importance of the shroud, hub and blade profiles as well as the surface finish. While the inlet and exit geometries are certainly critical, it is equally important that the remainder of the impeller flow passage geometry be held to within reasonable tolerances and that the aero flow path surface finish be consistent with those assumed during the design process. Changes in the hub or shroud profiles that cause deviations in the passage area can impact the capacity and head generating capability of the impeller. Rougher than expected surface finishes can have a detrimental impact on the impeller efficiency, causing increases in overall power consumption in the compressor (Childs & Naronha, 1997 and Cousins et al, 2014).

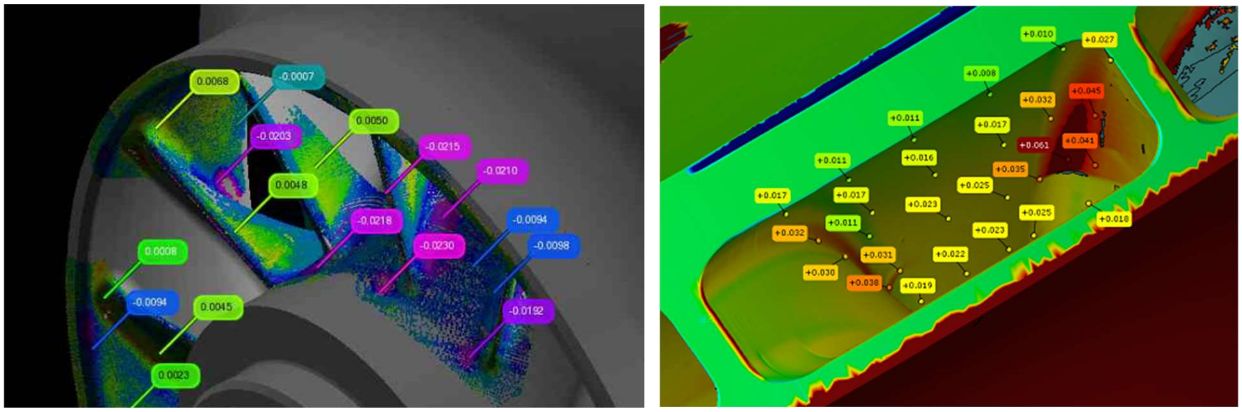


Figure 8 – Laser scan data at impeller inlet (left) and exit (right)

Before addressing materials and the various methods used to manufacture centrifugal compressor impellers for typical industrial applications, it is important to note that there are two basic styles of impellers applied; the open or unshrouded impeller and the covered or shrouded impeller as shown in the photos below (see Figure 9). Clearly, the manufacturing process is somewhat easier if there is no shroud or cover. However, even open impellers can be a very complex machining as seen in the center photo of Figure 9.

Figure 9 – Impeller Types – Unshrouded at left and center – Shrouded at right

Key Materials Considerations

When considering the materials used to build impellers, it is important to address the impact of NACE, the National Association of Corrosion Engineers. Established in 1943 and currently known as NACE International, this professional organization is responsible for developing corrosion prevention and control standards. The impact of these standards have greatly affected impeller manufacturing and design. The two standards which have had the greatest impact are NACE MR0175/ISO 15156 and NACE MR0103/ISO 17945. This tutorial will not go into details about the development of the standard, but an overview is provided on how the standards impact material consideration for impellers.

The NACE 175/103 standards provide guidance and limitations on materials that can be used in gas environments containing hydrogen sulfide (H_2S). Materials improperly used in H_2S environments can experience stress corrosion cracking (SCC), which is a mechanism that can propagate cracks in material that are under tensile loading even if the stresses are below the conventional design limitations. NACE 175/103 provides environmental, mechanical, and heat treatment condition limitations dependent on material grades and microstructures (ie. Carbon and low-alloy, or martensitic stainless). Compliance with NACE 175/103 is generally a requirement specified by clients, and/or required by the OEM's internal guidelines. Other industry standards can require compliance if the field operating conditions align with those covered by the standards.

The environment limitations start with the initial material selection for the impeller based on the expected gas environment, pressure, and temperature. Once the expected gas environment is calculated, an evaluation of materials based on the physical properties can be done. The mechanical limitations vary from, predominantly, Rockwell Hardness to yield strength based on the material grade (i.e., Duplex stainless steels will have different limits than Austenitic stainless steel). Even after a material is found that is acceptable for the expected environment and mechanical limitations, the material can only be used if the proper heat treatment is applied to the impeller. This is to ensure that the material is free from potential harder areas within the material. These harder areas could arise due to microstructural phase transformations or due to manufacturing process steps.

Another key materials-related issue is the impact that joining processes have on mechanical properties. Many of the manufacturing processes still in use today include welding. Welding creates a diverse set of mechanical properties across the joint. There are three different areas within a welded joint: (1) an area with a cast-like microstructure where the molten material solidified, (2) a heat affected zone which reached a temperature high enough to experience a microstructural phase transformation but not high enough to liquefy, and (3) the base material which was unaffected by the heat of the joining process. The impellers joined via welding requires specific heat treatments to ensure that the hardness profile of the welds comply with the mechanical limitations because the heat effect zone and weld metal tend to have a higher hardness than the base material. It is important to note that using brazing as a joining method is advantageous because brazing does not impact the strength of the material near the brazing material, i.e., there is no "heat affected zone." However, an important consideration in brazing is selecting the proper brazing material that has mechanical properties which meet engineering requirements and has a melting point that is not detrimental to the base material.

It is the authors' experience that as the methods used to predict stress levels continue to improve, designers are beginning to bump up against material limits. Further, some impeller designs require tighter control of the joining and heat treatment operations to ensure a quality product. This has led to a need for testing materials in increasingly sour environments and to push the control of the mechanical properties to tight tolerances.

Having addressed the important areas, the styles of impellers that must be built, and key materials considerations, the remainder of the paper will concentrate on the types of manufacturing processes applied.

IMPELLER MANUFACTURING

The advancements in engineering simulation and modeling tools described above have had a direct impact on impeller manufacturing techniques. These techniques have advanced since the first centrifugal compressors were built at the beginning of the 1900s. In the eyes of the manufacturer, there are two main topics that push manufacturing to evolve: Cost and Cycle Time. Of course, to be competitive in today's turbomachinery industry, accuracy and repeatability are also important. Without the latter, it would be impossible to provide accurate performance predictions to or instill confidence in those who purchase the compressors.

Cost can be affected by many attributes: an operator or machinist charging too many hours, the process causing too many Non-Conformances, inexperience or incompetence leading to too much scrap, or even the simple theory that the current method of manufacture cannot meet the engineering requirements that the engineering simulation tool has presented. Cycle time issues mirror that of the cost, however, it is the disposition of all issues that increases cycle time. If an impeller cannot be delivered on time in a cost-effective manner, the process or technique must change or evolve.

The various techniques will be presented in chronological order as experienced by the authors' company. Other OEMs might have introduced these and other techniques in a different order. There is no perfect, one, end all be all, way to manufacture an impeller. Each technique has its place in manufacturing, however when customer requirements and engineering push the technique to its limit, the next greatest method must be adopted.

Riveted impellers

Many of the earliest impellers built for industrial compressors were of riveted construction. There were two basic styles of riveted impellers used: "Z" or "U" bladed (or "rivets through flange") and "through blade riveted".

"Z" or "U" bladed riveted

The blades were formed from sheet metal or plate material and riveted to both the disk and cover. These were characterized as "three-piece riveted" construction. The blade thicknesses were based on standard material sizes, i.e., 0.060", 0.090", 0.120" plate, and the blades had so-called "flanges" on each side (hub and shroud). If the flanges were bent in the same direction, this was commonly called a "U" blade. At the authors' company, the flanges were bent in opposite directions forming a "Z" shaped blade as shown in Figure 10.

Figure 10 – "Z" blade – note flanges in photo at left and "Z" shape in photo to the right

Holes were drilled in the flanges as shown and matching holes were drilled (or milled) through the adjoining shroud and hub. The blades were then riveted to the hub and shroud (typically in that order) to complete the impeller. The rotor shown in Figure 11 includes two “Z”-bladed riveted impellers to the right in the photograph. The rivets are clearly visible in the impeller to the far right.

In the early 1900s, the authors’ company built numerous steel mill blast furnace blowers with “Z”-bladed riveted impeller in excess of 70” (1780mm) in diameter. There are still machines in operation today that have impellers that were built using this approach.

This construction method can be labeled as very labor intensive and the blade manufacturing itself takes skill and dedication to create exactly what the engineer needs. Many have been replaced over the years with welded impellers.

Through blade riveted

In the “through blade” blade riveted style, the blades were most often machined to the hub and holes were drilled through the center of the blades to accommodate the rivets. In this method, the impeller blades had to be thick enough to accommodate the holes while leaving sufficient material surrounding the hole to provide strength. The rivets were inserted through the aligned holes in the bladed hub and the shroud and peened to complete the construction (see Figure 12). The “through blade” riveted impeller blades were typically 2-D shapes, i.e., circular arc with no blade lean, to facilitate the riveting process. Referring again to Figure 11, the impellers at the left end of the rotor are “through blade” rived impellers. Note that there is no “Z” shape to the blade and upon close examination, one can see the indications of the rivets in the cover of the impeller to the far left.

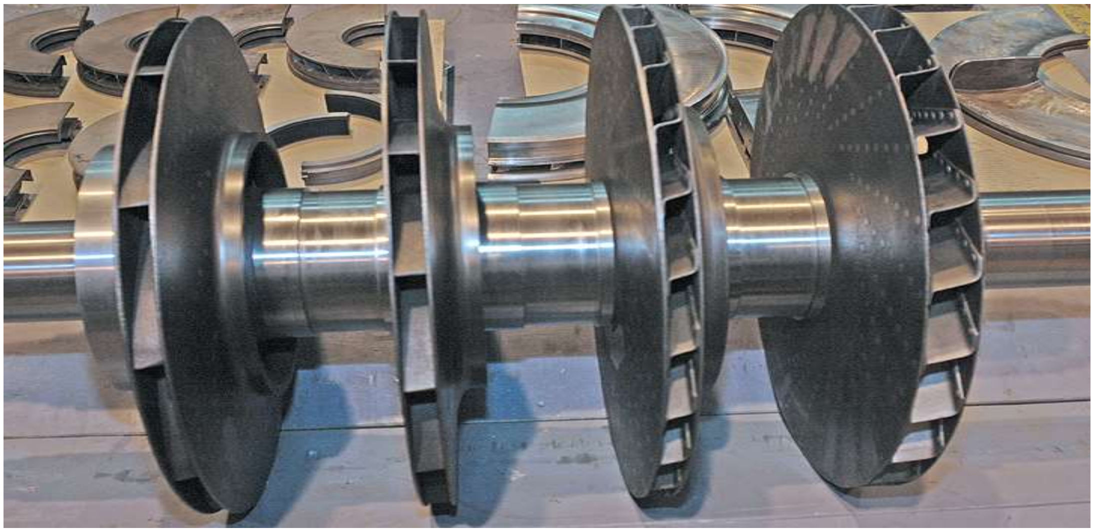


Figure 11 – Rotor with riveted impellers (“through blade” to left and “Z” blade to right)

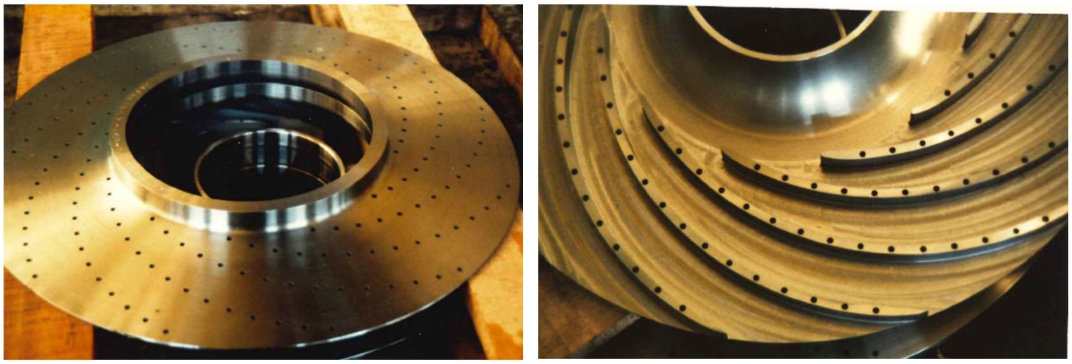


Figure 12 – Through blade riveted impeller (cover at left, bladed disk at right)

The blade forming and riveting processes limited the blade shapes that could be applied in riveted impellers. This constrained the achievable aerodynamic performance. The strength or robustness of the impeller was also compromised because of the rivets. It was the latter consideration that led to the eventual move away from the riveted construction.

The riveted impellers cause a few material concerns that had to be accounted for. Rivets that were improperly peened could create additional mechanical loading which could lead to crack formation via fatigue. The quality of the rivets had to be closely monitored and qualified to ensure the rivet was peened properly.

When using riveted impellers in corrosive environments additional care had to be used when selecting the proper material alloy. Since there are gaps between the cover and the disc of the impeller, corrosive elements could build up and cause greater amounts of corrosion. These areas could create a stress riser, which would allow a fatigue crack to propagate and damage the impeller.

Cast Impellers

To overcome some of the limitations of riveted impellers, some OEMs turned to cast impellers. Casting allowed for more complex impeller blade shapes, providing some improvement in the aerodynamics of larger flow coefficient impellers. However, pattern costs and the quality of the finished product (i.e., geometric accuracy and surface finish) using the casting methods available in the middle of the 20th century caused many OEMs to abandon castings, especially as welded impellers became more prevalent in the 1960s. Due to the combination of thick and thin areas, casting an impeller was not an easy task. This method was historically called the "four for one method" because it has been the authors company's experience, as recently as the early 1990s, that four castings would have to be poured to get one acceptable piece. Many defects in the casting include, but are not limited to, voids in the casting, surface finish issues, and cracking etc. However, as will be addressed in later sections, as casting methods improved beyond the old sand cast approach, cast impellers again became a viable alternative, especially when making multiple copies of a particular impeller design or bladed disk. In fact, the authors' company now regularly produces pump impellers that are built using precision casting methods.

In general, nearly all cast impellers used by the authors' company are outsourced to a casting vendor and post-processing is done in-house to create the finished impeller. An impeller drawing providing the critical engineering dimensions is created and provided to the casting vendor, who uses their modeling techniques and "tribal knowledge" to develop patterns and use the proper casting methods (i.e., improved sand casting, investment casting, lost foam casing, etc.) to ensure the cast piece meets the quality and mechanical property requirements. Some of the various methods used are now described.

Sand casting is a process which first requires a pattern be developed that replicates the final part. A box is filled with a sand mixture (sand with clay, binders, or oils) and compacted much like a sandcastle you would make at the beach. The box is traditionally in two halves. The pattern is used to create an impression in the sand and then removed from each half of the box so that when the halves are placed together, there is a void in the sand or mold cavity that resembles the pattern. Molten metal is then poured into the mold to form the cast part. It takes great care, knowledge and experience to develop a pattern that will yield an accurate cast part.

Investment casting is similar to sand casting, but the pattern is made from a material with a low melting temperature, typically wax or some other polymer. The pattern is then dipped into a slurry of refractory multiple times to build up a ceramic shell on the outside of the pattern. The whole assembly is put into a low temperature oven and the wax is melted from within the ceramic shell. The molten metal is then poured into the void and a casting is created. The authors' company used this method for several years to build return channels for small frame-size compressors because of the improved surface finishes obtained using this approach.

Lost foam casting is a hybrid of investment and sand because the pattern is encased in sand or a ceramic slurry. The pattern is built using a foam material and left within the sand or ceramic. When the molten metal is poured into the sand or ceramic pattern, the foam evaporates.

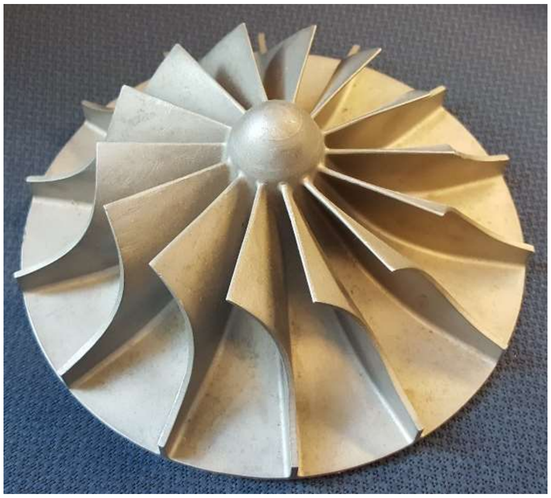


Figure 13 – Unshrouded cast impeller

With all of these casting techniques there are multiple other components required (risers, vents, pouring cup) and the size and location of those components are important in obtaining a quality casting. Risers are areas which hold excess molten metal which helps reduce the impact of shrinkage due to cooling. During the liquid to solid phase transformation metal loses a percentage of its volume and the proper anticipation will prevent any defects from forming. The depth of knowledge required to obtain a high-quality cast component is why the authors' company has chosen to rely on casting suppliers for cast components rather than attempting to maintain that expertise in-house.

Open or Unshrouded Impellers

In many early applications, it was possible and often preferred to use open impellers, i.e., impellers with no cover or shroud. In the early years, such impellers were sometimes cast (see Figure 13) but also welded. When cast, the impeller was a single piece with the blades cast integral with the hub. Pattern costs and geometric and surface quality were a concern so many OEMs began fabricating open impellers by forming the blades from plate (see Figure 14) and fillet welding the blades to the hub. Several approaches were used to form the blades. In some cases, die blocks were developed and the blades were cold or hot formed in a hydraulic press. In other cases, the plate was formed using a "black smith"- like approach, i.e., the blades were heated and hammered into the necessary shape (either with hammers or a press break). The blades were checked "in process" against a check block built from wood or other material. Once the necessary set of blades were formed, various types of blade locators (see Figure 15) were used to hold the blades in place while they were welded to the hub (or disk).

Figure 14 – Impeller blade formed from plate

Figure 15 – Locator positioning formed blade on hub for welding

A concern associated with the welded open impeller was deformation of the blading or the hub due to the heat input from welding. Residual stresses in the materials would be relieved during the stress relieve or heat treat operations and could cause the impeller geometry to deviate from or fall outside of the design specifications There could also be concerns regarding the heat affected zone on the blades and disk that could compromise the strength or robustness of the part.

The methods of forming blades required many hours of manual labor and the blacksmithing of such blades required a skill that takes countless hours of training and practice. Throughout the years, this skill has been lost, along with most of the forms and blade locators. Much faster, cost effective means of manufacturing were quickly produced to replace this technique.

Milled Open Face Impeller

The issues related to welding were for the most part alleviated with the introduction of 5-axis milling in the 1980s. This eliminated the need for any welding on open or unshrouded impellers. This also allowed more exotic blade shapes to be machined rather than formed, resulting in much more accurate blade shape and smoother surface finishes. The level of deformation occurring during stress relieve and heat treat operations also reduced because the residual stress from the heat input during welding was eliminated.

It should be noted that the more sophisticated blade shapes also resulted directly from advancements in the design software developed in the 1960s through 1970s. These systems allowed aerodynamic designers to move beyond blade shapes specified via geometry surfaces (i.e., cones, inclined cylinders, etc.) and define blade shapes using line elements in space or coordinate matrices.

Figure 16 – 5-axis milled open impeller

Manufacturing Shrouded / Covered Impellers

Shrouded or covered impellers are built using a large number of different processes. In principle, they can be divided into three categories: three-piece construction; two-piece construction and single-piece construction. The methods were effectively developed and, therefore, will be addressed in that order.

Three-piece construction – Fillet-welded

Three-piece construction via riveting has already been addressed and the majority of other three-piece construction impellers were built via fillet welding. In general, the three-piece welding method followed a process very similar to the "Z"-bladed riveted impellers. Like the "Z"-bladed riveted impellers, the blades in three-piece welded impellers are formed separately (revisit Figures 13) and then welded in place. The blades are formed using the same processes described for the welded open impeller and, likewise, locators (revisit Figure 14) are used to properly position the blades for welding. In the normal process, all blades are first tack-welded to a ring that puts them in the proper position for welding to the cover. The blades are turned on a lathe to match the cover contour and the cover is welded in place. Next, the hub side of the blades are turned, and the blades are welded to the hub. This can be a very time-consuming process. The welding torch must be inserted into the impeller passage and the weld bead properly laid down in the blade – hub interface on both sides of the blade. The photos in Figure 17 show various steps in the process. The blades are being tack welded to the ring in the picture at left. The blades have been spot welded to the cover in the center photograph and a finished three-piece welded impeller is shown at the right.

Figure 17 – Various steps in three-piece welded impeller assembly.

Over the years, several issues were encountered with three-piece welded impellers. As with the welded open impellers, geometric deformations occurred because of the heat input in laying down all of the welds to construct the part. These would often come to light after the stress relieve and heat treat process. Further, if inadequacies in the welds were identified during inspection (via dry mag or wet mag methods), the defective areas would have to be ground out and re-welded. This also resulted in a need to re-heat treat the part and further deformation could result.

The material selected also played a big part in welding and manufacturing difficulties. Alloy grades which air harden easily created hard weld joints which, if not properly handled, could crack before completion of stress relief. The manufacturing steps had to be altered depending on which alloy was being welded due to the additional stress caused by welding the cover to the blades. The discovery of these difficulties sometimes came iteratively with specific situations (i.e. thinner blades versus thicker blades). Other alloy grades, which have a lower temperature phase change or a retained microstructure, can cause additional deformations which were difficult to anticipate.

Two-piece welded construction – Fillet-welded

The initial efforts on two-piece construction consisted primarily of simpler, 2-D blades, such as circular arc sections, that could be machined on 3-axis mills. The cover was then fillet-welded in place with the same welding equipment that was used for the three-piece welded impellers. As 5-axis machining methods were developed, it was also possible to machine more complex blade shapes integral to the hub or shroud and then fillet-weld the shroud or hub in place. The two-piece welded impellers experienced fewer distortion or deformation issues during stress relieve and heat treat because there was much less welding done on the assembly. Further, because the blades were machined, the geometric accuracy blade-to-blade was much higher than in the three-piece welded construction. However, the fillet-welded approach did provide some concerns and limitations. One limitation was related to the ability to get the welding torch into the impeller passage. If the passage height in the impeller was too short, it was not possible to fillet-weld the assembly. This limited or eliminated the ability to fillet-weld low flow coefficient impellers with their inherently narrow flow passages. In general, if the impeller passage height is less than 0.75” (19mm), it is difficult to ensure a quality fillet-weld. Likewise, in some impellers, it was not possible to reach portions of the impeller passage from either the impeller exit or the inlet due to the curvature of the cover and/or blade. At this point, the OEM either had to accept an assembly that was only partially welded, or they had to find other joining methods.

Fillet-welding can also create surface imperfections caused by weld splatter. Further, the weld bead itself is often be rough and/or inconsistently sized. In response, the impeller passages are often grit-blasted and the fillets ground to remove the imperfections. However, both corrective measures can degrade the surface finish of the impeller passages, which will cause more friction losses in the impeller. Additional corrections, such as extrude honing or slurry-finishing, can be done to achieve the necessary finish for good impeller performance.

As noted earlier, any deviations in the impeller exit area can impact its ability to generate head or pressure ratio. In a fillet-welded impeller, the weld fillet blocks a portion of the flow passage (see Figure 18). Therefore, if the performance prediction does not properly account for this fillet blockage, the result will be an erroneous estimate for the head level of the impeller. Further, if this fillet blockage also reduces the impeller throat area, the overload capacity would also be compromised. Note: These same considerations are true for machining fillets (the radii between the blade and cover or blade and disk).

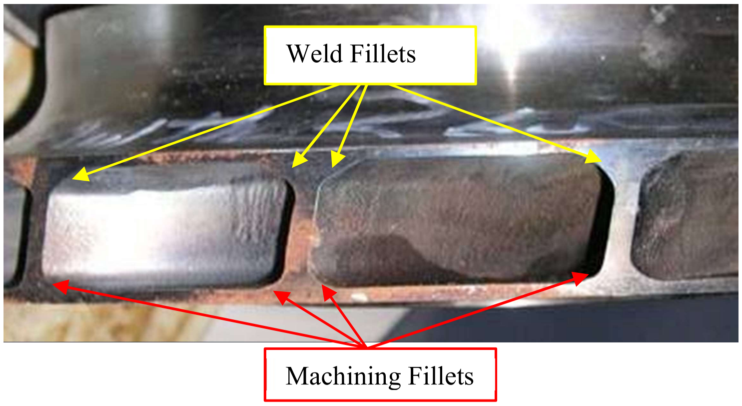


Figure 18 – Weld and machining fillets at impeller exit

While on the subject of machined surfaces, much attention has been given on the potential impact of machined surface on turbomachinery performance (Childs and Noronha, 1997, Cousins et al, 2014). Of particular interest are the machining grooves or serrations that appear on blade, hub and shroud surfaces caused by point milling (using the end of a cutter as shown in Figure 19) rather than flank milling (using the side of the cutter). There are conflicting opinions regarding the impact of these grooves as some see them as advantageous while others see them as a detriment to performance. Most OEMs (including the authors’ company) have specifications limiting the height of these ridges or serrations. The limits are based on their test experiences with varying ridge sizes and on the cost trade-offs associated with the time (extra machining passes) on the mills to eliminate the ridges.

Figure 19 – Point milling blades integral with hub – See milling ridges / serrations at

Two-piece welded construction – Slot-welded

As noted above, as the demand grew for smaller compressor frame sizes and lower flow coefficient impellers, the impeller passages became too narrow for fillet-welding. Therefore, OEMs developed other joining techniques to be able to accurately construct impellers with these narrow passages. One such technique is slot-welding. In this approach, a slot is cut in the impeller hub (or shroud) leaving a very thin layer of the base metal (see Figure 20). The blades are machined integral with the shroud (or hub). The blades are then positioned against the base metal remaining at the bottom of the slot in the hub (or shroud). Weld metal is then "puddled" into the slot, melting the remaining base metal at the bottom of the slot and forming a bond to the top of the blades.

Figure 20 – Impeller construction via slot-welding

Slot-welding has been used extensively since around 1975 for low flow coefficient designs and is still in use today for some impeller applications. However, there are some issues related to what has commonly been described as non-uniform "shrinkage" in the impeller passage. This causes the impeller passages to be slightly smaller than expected or specified. While not of concern for most impellers, it can be a problem for extremely narrow passages. The "shrinkage" can be as much as 0.030" (0.75mm), so it can be a large percentage

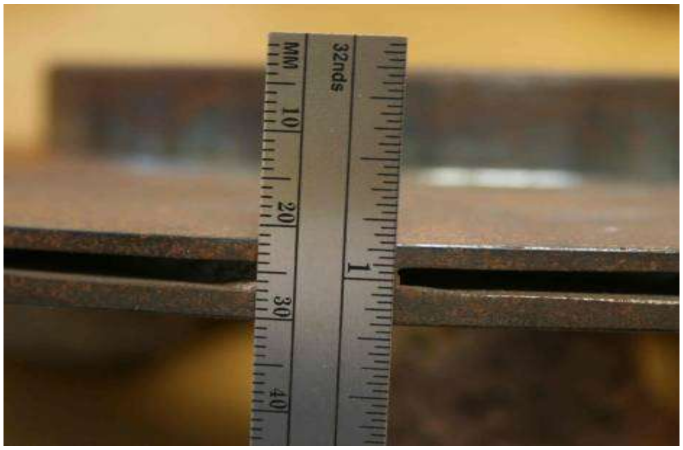


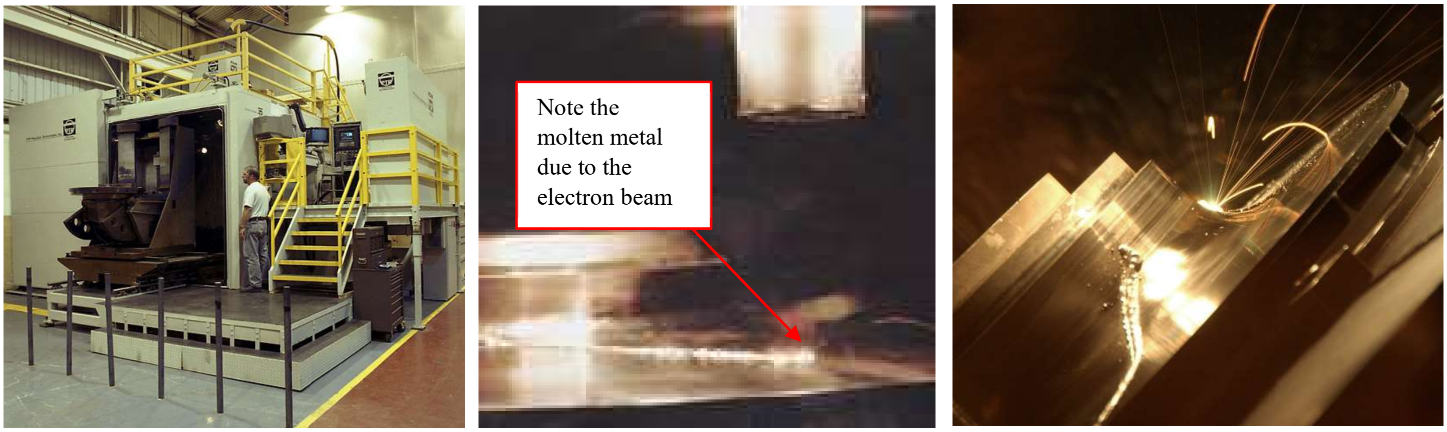
Figure 21 – Impeller with very narrow blade height – 0.11" (2.8mm)

of the passage height on very narrow designs (see Figure 21). This reduction in passage height changes the capacity and the head generating capability of the impellers and if not properly addressed will cause machines to fall short of performance requirements.

There have also been issues with "dishing" or "potato-chipping" of slot-welded impellers due to the amount of welding required. This causes the impellers to deform in an umbrella-like manner. This can cause issues if proper adjustments are not made in the final machining of the outside surfaces or if the impellers are not "straightened" during the stress-relieve or heat treat operations. The choice between putting the slots in the shroud or in the hub is driven by the position of the impeller blade leading edge. If the leading edge is parallel to the shaft (i.e., the hub inlet radius and shroud inlet radius are equal), the slots are typically cut into the hub. However, if the shroud leading edge radius is higher than the hub inlet radius, the slots are cut into the shroud.

Two-piece welded construction – Electron beam welding / Brazing / Ebrazing

Given the concerns regarding the shrinkage of slot-welded impellers, other techniques were developed to eliminate or at least minimize these issues. The three techniques most commonly applied are electron beam welding, oven brazing, and Ebrazing, which is a combination of electron beam welding and brazing that was developed by the authors' company in 1999.



Note the molten metal due to the electron beam

Figure 22 – Electron beam welding system at left – Impellers being EB-welded at right

Electron beam welding (or EB-welding) is very similar in concept to slot-welding except that there is no slot cut into the shroud or hub. Instead, the electron beam penetrates the surface being joined to the blading and the blading itself, melting the base metal of both to form the bond. EB-welding is done in a vacuum to eliminate any potential deflections of the beam due to the presence of any gas. An example of an electron beam system and photograph of an impeller being EB-welded are shown in Figure 22. The authors' company used this process in the 1970s through the 1990s to build the impellers for certain products. The blades were cast integral to the disk and the covers were EB-welded in place. Therefore, it was a unique combination of casting and electron-beam welding.

The EB joint was formed in the center of the impeller blade, so there was a "mechanical stop" that kept the impeller passages from shrinking, thus eliminating one of the drawbacks of the slot-welded approach. However, some expressed concerns regarding the unattached portion of the blading on either side of the EB joint. It was feared that this represented "cracks" or flaws in the joint that could lead to fatigue-related issues. This concern led to the development of the electron-beam welded / brazed or EBraze$^{\text{TM}}$ process.

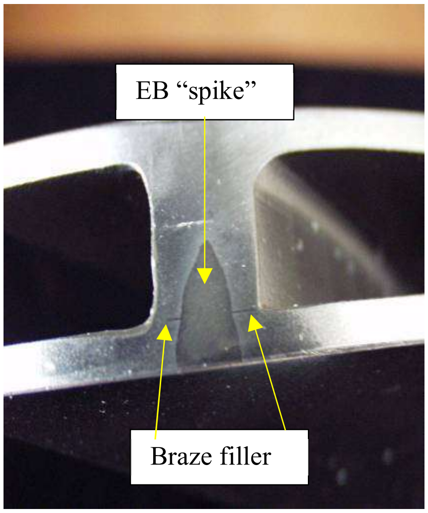


Figure 23 – Close-up of EBraze$^{\text{TM}}$ joint (surface etched to enhance view of joint)

EBrazing is effectively electron beam welding with the addition of a layer of braze material along the top of the impeller blade so that a braze joint is formed during the EB-welding process (Miller et al, 1996). This joins the portion of the blade surface that had been unattached after EB-welding, thus increasing the fatigue resistance of the joint (see Figure 23).

It is important to note that the EB-welding system can limit the impeller diameter because of the size of the vacuum chamber. There are also minimum impeller blade thickness requirements to ensure that the electron beam does not burn through the side of the blading. These limits are a function of the width of the beam, any beam dithering that is used, the beam intensity, etc. This can also impact the size of the impeller than can be EB-welded because it might not be possible to EB-weld smaller diameter impellers because the blades would be too thin.

From a metallurgical perspective, the characteristics of the EBrazing joint are similar to a welded joint: an area with a cast like microstructure where the molten material solidified, a heat affected zone which reached a temperature high enough to experience a microstructural phase transformation but not high enough to liquefy, and then the base material which was unaffected by the heat of the joining process. After proper post-processing the joint results in a strength equal to that of the base material without sacrificing ductility. In order to achieve the desired mechanical properties, the braze metal has to have a very specific melting point and mechanical properties to ensure the mechanical properties of the base metal and the joint ductility are achieved.

Finally, it is possible to create a strong joint with brazing alone (see Figure 24) and that starts with the selection of the brazing alloy. The braze alloy must melt at a temperature where the impeller material is not negatively impacted (i.e. if the melting temperature is too high, the metal could melt or soften to the point that unacceptable geometric distortions would occur). It is equally important that the braze material remain solid if subsequent heat treatment operations are required. Gold and nickel with specific amounts of alloy to control the liquidus (temperature at which the material melts) and solidus (temperature at which the material solidifies) temperatures can be used for brazing steel alloys. The strength of the joint depends on the brazing technique and braze material used because the braze is essentially the "glue" between the two components holding the part together. Controlling the braze foil thickness and time at the brazing temperature can also impact the strength of the joint.

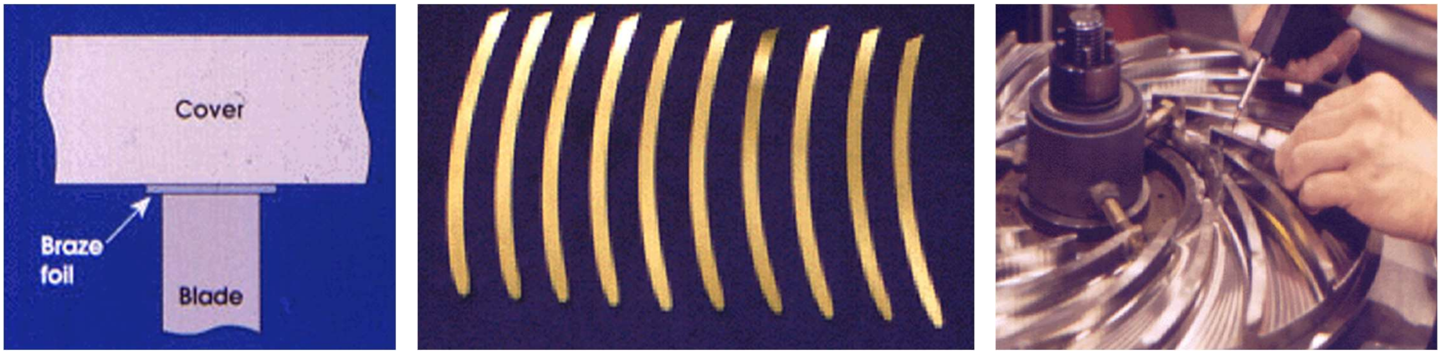


Figure 24 – Braze joint schematic at left – Braze foils in center – Braze foils being placed on impeller blades at right

Brazing requires very precise dimensional agreement between the top of the blade and the surface (hub or shroud) where the joint is being made. If the gap is too wide, the joint will be weakened and the shroud (or hub) could separate from the blade. This could be catastrophic were this to happen in field operation. Therefore, as with all impellers, brazed impellers are overspeed tested in spin pits to rotational speeds higher than the rotor will operate at the client facility, ensuring that the joints will not separate in field operation.

Note that the authors' company does brazing for a large number of impellers provided to clients. In fact, depending on the service and/or the size of the impeller, a given impeller design can be electron-beam welded, brazed or Ebrazed with no impact on the aerodynamic performance of the impeller.

Note: There are other manufacturing methods that fall under the category of two-piece construction but those will be addressed under the single-piece that follows.

Single-piece construction – Milled

Just after the year 2000, many OEMs and machine suppliers began working on single-piece milling of covered impellers (Sorokes & Kuzdzal, 2010, Cave & Ji, 2017). The impellers were milled from a single forging, totally eliminating the need for any joining process. The strength and fatigue resistance were increased significantly.

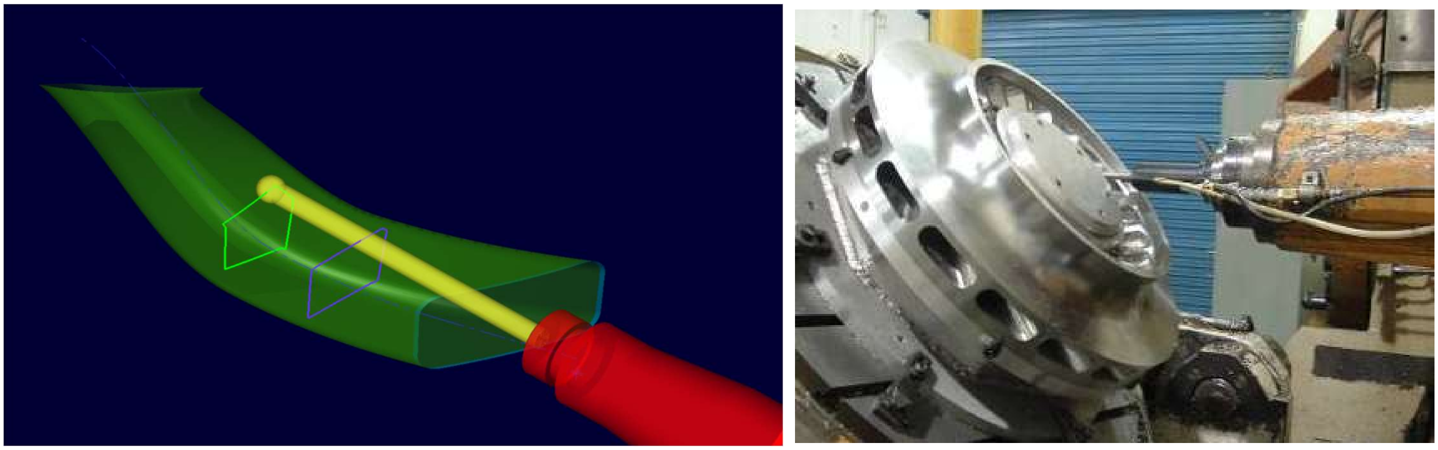


Figure 25 – Simulation of cutting from exit at left – Photo of machine cutting from inlet at right

Under this process, material is removed both through the exit and the inlet of the impeller and the milling processes meet somewhere in the middle of the passage (see Figure 25). Special cutters, similar the one shown at the left in Figure 25, were developed to make it possible to mill somewhat around corners. Despite this, there are still factors that limit what impeller geometries can be successfully single-piece milled.

First, it must be possible to reach all the locations that must be machined. This means that there must be "line of sight" to all machined surfaces. Second, there are limits to how long a cutter shank can be as a function of its diameter. This limits how deep a cut can be into an impeller passage. Also, the longer the cutter, the greater the likelihood that chatter or tool deflection will occur, causing inaccuracies in the passage surfaces. Third, because the cutter shaft must be robust enough to rigidly support the cutter at the end, it can become a limiting factor in determining cutter access. If the shaft or shank contacts any surfaces as the cutter is extended into the passage, it can cause damage to the blade, hub or shroud. Also, all three of these considerations contribute to a longer cycle time on a milling center. This directly correlates to an increase in cost, which, in some instances, makes the two-piece fillet welded impeller a more viable option.

It is also necessary to consider the milling time required for single-piece construction and the non-recoverable engineering costs to program the machine tool. As a result, single-piece milled impellers can be quite costly. However, the extra robustness and fatigue resistance achieved might justify the extra cost, i.e., if an OEM or end user can eliminate impeller failures in the field.

Sidebar – A Quick Return to Two-Piece Construction

In the above discussion on single-piece milling, it was noted that "line of sight" or cutter access to the machining surfaces is required. In some impeller configurations, this is impossible. However, it might be possible to achieve cutter access or "line of sight" if a portion of the hub is removed (Ranz & Seib, 2011). In most situations, the "hard to reach places" can be accessed if a portion of the hub (or so-called "cover plate") near the impeller exit is removed. The remainder of the impeller passage can then be milled from a single forging. Once the milling process is complete, the "cover plate" can be EB-welded, EBrazed or fillet-welded in place. The impeller is then finish machined on a lathe and the impeller is ready for service. The images in Figure 26 will help the reader visualize this process.

Figure 26 – Graphic rendition of cover plate and single piece section at left – Single piece machined section in center -- Photo of impeller with cover place EB-welded in place at right

Single-piece construction – milling & EDM

In some situations, it is possible to single-piece mill the majority of the impeller flow path and use electro-discharge machining (EDM) to finish those locations in the impeller that cannot be reached via milling. Special electrodes are developed that are able to "burn out" the "hard to reach" places within the impeller passage. The authors' company has worked with a third-party supplier to build several production impellers using the combined milling / EDM approach.

It is also possible to use EDM to create the entire flow path. This process is described in detail in Yang et al (2013). In this case, EDM "cutters" of various shapes and sizes replace the typical milling cutters to remove material via the inlet and exit openings of the impeller and, as noted above in the discussion on single-piece milling, meet in the middle of the passage. This can be a very time-consuming and costly process and the authors' company has found the combination of milling and EDMing to be more cost-effective.

From a metallurgical perspective, EDMing does result in a re-cast layer of material surrounding the region that was machined. The recast layer contains a layer of solidified molten material which is detrimental to the mechanical properties of the base material. The recast layer can be removed via various methods (i.e., extrude honing, slurry finishing, grinding). This material removal must be accounted for during the design and manufacturing process.

Single-piece construction – Plunge EDM

It is also possible to construct impellers via plunge EDM (Yang et al, 2013, Laney et al, 2016). In this case, special EDM electrodes are created that are approximately the shape of the impeller passage and each passage in the impeller is "cut" by plunging the electrode in from the impeller exit (see the photo at left in Figure 27). This approach has been around since the early 1980s. The authors' company experimented with this method on impellers for a small barrel-type compressor (see the photo at right in Figure 27). The process was also used to correct for the "shrinkage" experienced in slot welded impeller. More recently, with the advances made in EDM methodologies, this process is again being considered for fabrication of low flow coefficient impellers.

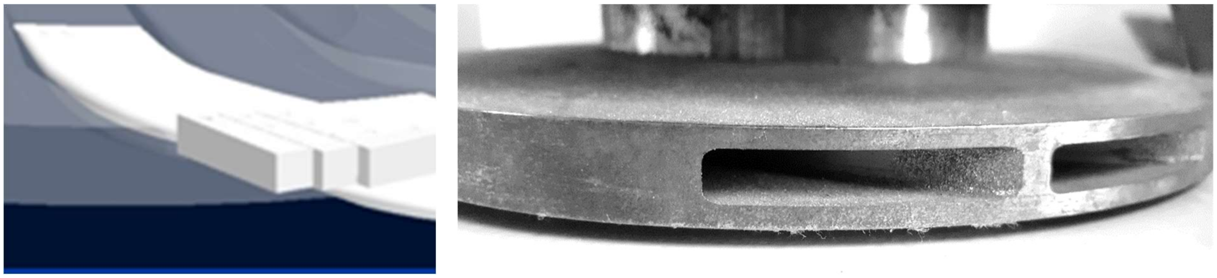


Figure 27 – Schematic of Plunge EDM electrode at left – Impeller built with plunge EDM process at right

Again, one concern with this process is the recast layer created via the EDM process, but a better understanding of the recast layer and its causes has helped improve the process and decreased the thickness of that layer to reduce the impact on mechanical properties. There is also some concern about the surface finish that results. Therefore, impellers built using this process will likely require some surface treatment, i.e., extrude honing or slurry finishing to address the surface finish and recast layer.

CURRENT / FUTURE DEVELOPMENTS

Compressor OEMs are continually searching for more advanced techniques for impeller manufacturing and many are currently investigating some new and promising methods. Some of the more promising approaches will be addressed in the remainder of the paper.

One-Piece Construction via Additive Manufacturing

One of the more exciting is additive manufacturing, more common called 3-D printing. There are a wide variety of additive manufacturing methods being developed with the technology evolving on a daily basis. This topic continues to receive significant attention in the open literature and is the subject of lectures at the TurboPump symposium. Therefore, details on the various alternatives will not be discussed herein.

Additive manufacturing offers significant opportunities to improve the aerodynamics and mechanics of impellers because it does not constrain the designer in ways that normal manufacturing processes do. With additive manufacturing, it is possible to include voids otherwise solid pieces to reduce weight and improve rotordynamics. It also does not constrain the aerodynamic designer to create impeller passages that can be machined via conventional methods. For example, it would be possible to create flow passages that do not require "line of sight" or that can be accessed via cutters or EDM electrodes. The flow passage can literally be almost any shape that can be conceived. Further, additive manufacturing allows parts to be built from materials that are difficult to use in other manufacturing methods.

Additive manufacturing does have its limitations. One major consideration is the limited size of parts that can currently be printed with many of today's technologies. Most are incapable of printing impellers larger than 16" (400mm) in diameter. However, if the need is for small diameter impellers, these can be done today. Another issue is the surface finish of the parts that are printed. Most have finishes similar to cast parts, but, again, surface treatments can be applied to correct this issue. Additive manufacturing also requires a change in thinking in the way the part is printed. For example, it is difficult to print unsupported surfaces, so support structures must be designed into the printing scheme. As an example, the impeller shown in Figure 28 was 3-D printed. The arrows in the figure show the surfaces that might have been unsupported during the printing process depending on the orientation of the part when it was printed. Any such areas or features would have had structures printed into the part and said structures were removed after the printing process was completed. This does result in wasted material but much of that can be re-used in building future parts.

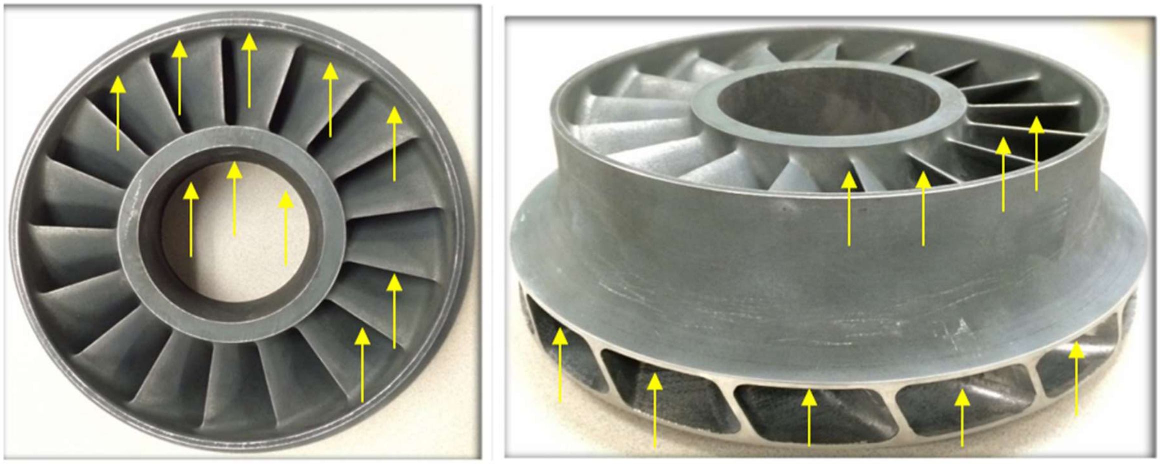


Figure 28 – Impeller build via additive manufacturing – Yellow arrows point to potentially unsupported surfaces depending on part orientation during printing process

Due to the layer-based construction of additive manufacturing the material can experience anisotropic mechanical properties. This can be managed by printing the part at different angles to ensure the loading of the part aligns with the desired mechanical properties. Printing at these angles increases the amount of supports, time, and post processing required to create a part.

One-piece construction via powdered metal

The powdered metal construction process in many ways is like casting (Ramakrishnan, 1983). The process is described in detail in Laney et al (2016). Summarizing the approach, similar to casting, a solid "pattern" is created that closely replicates the impeller flow passages. This "pattern" is machined or built from a material that is more brittle or much less impervious to acids than the material that will be used for the solid portion of the impeller. This "pattern" or "insert" is then mounted in a canister that forms surfaces near the desired outer surface of the impeller. Powdered metal is then poured into the canister and the canister is hot, isostaticly pressed (HIP'ed) to solidify the powdered metal around the "insert" and the shaped inner walls of the canister. The canister is then removed revealing the solidified impeller with the "insert" embedded in the impeller. The "insert" that formed the flow passages is then removed by vibrating the assembly or using acid or some other method, leaving the near-finished impeller. The outside and bore are then finish machined and the impeller is ready for use.

As noted, this approach is very similar to casting and the finished part is subject to many of the same issues that are found with cast impellers. These include rough surface finishes, imperfections in the material, geometric deviations, etc. Further, some experimentation is required to determine how much shrinkage or distortion will occur during the HIP'ing process. Therefore, this method might not be practical for "one off" applications, i.e., impellers that might only be used once or twice. However, if a large number of identical impellers are required, this approach can be economical.

Figure 29 – An impeller built from powdered metal

One-piece construction via hybrid casting

Referencing the third manufacturing method described in this paper, in the 1900s, casting an impeller was to be *the* way to manufacture an impeller. It allowed almost any geometry to be constructed. However, the cost of the patterns and related materials and the scrap rates were too high to be a viable long-term solution. A manufacturing method on the horizon of the author's company is called Hybrid

Casting. This method creates the mold or forms that will be used in the casting process via additive manufacturing. Therefore, the form is a fraction of the cost of the patterns that were used in older casting processes and the cycle time to build the forms is reduced from weeks to days. Once cast, the impeller will be HIPed, hand polished, and final machined. The casting itself still has the same material properties as more primitive castings. However, creating the impeller in a fraction of the cost and cycle time revives this method of manufacturing for a new era of impeller styles.

One concern of the older casting methods was geometric accuracy. Using this hybrid casting approach, the mold itself is more accurate resulting in a more accurate cast impeller. A laser scan of a hybrid cast impeller is shown in Figure 30. The values shown are within the engineering tolerance requirements for an impeller of the size built.

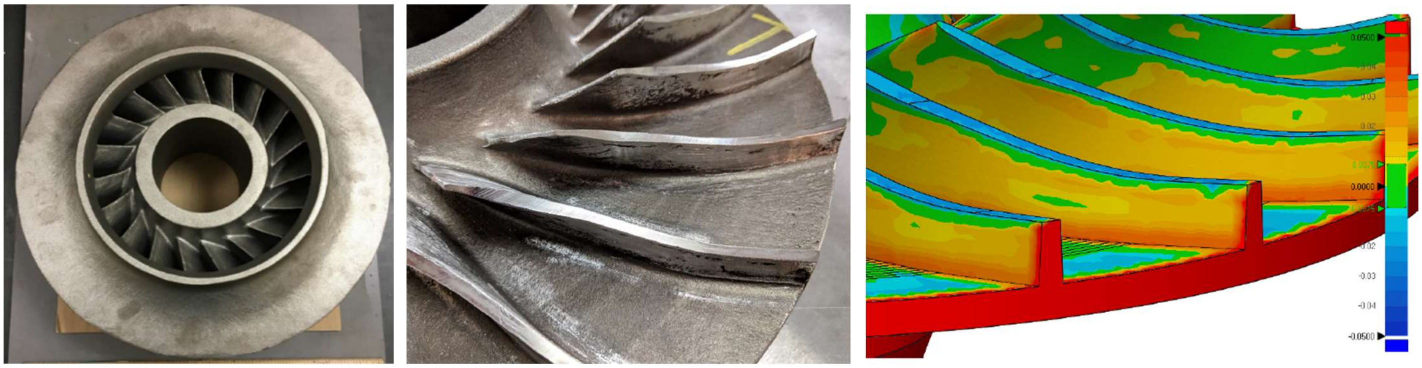


Figure 30 – Single-piece impeller at left – Blades with cover removed in center -- Laser scan data for hybrid cast impeller blades at right

This manufacturing method has yet to be fully vetted by this authors' company. However, the authors believe that this method is right on the cusp of entering the manufacturing world and should be watched closely as development continues.

CONCLUDING REMARKS

The paper has described some of the key parameters impacting centrifugal impeller performance and has reviewed some of the consequences associated with deviations from drawing dimensions. The various methods for manufacturing impellers were then offered along with commentary on their advantages and disadvantages. Comments regarding the impact of material selection were scattered throughout the discussion.

It is hoped this tutorial has provided the reader with insight into impeller manufacturing methods. It is possible that some methods were overlooked but these are the methods familiar to these authors. It is certain that more advanced methods will be developed in the future as OEMs and end users alike seek more robust and efficient machinery.

ACKNOWLEDGEMENTS

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