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EVALUATION OF VARIOUS METHODS FOR MANUFACTURING ONE PIECE, SMALL TIP OPENING IMPELLERS

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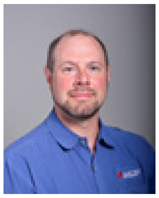

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ABSTRACT

Closed centrifugal compressor impellers have been manufactured using several methods through the years. Due to limitations of the materials and machining processes, most of these impellers have been manufactured in what is considered two piece or three piece methods. Despite the vast amount of experience with traditional construction methods, there is a drive to move towards one piece construction, where there are no joints and, in theory, lower probability of preexisting defects. Typically, the impellers that are being offered as one piece are those with relatively large openings where 5-axis milling machines can be utilized. This paper investigates several alternative methods to manufacturing small tip opening impellers as a single piece. The methods discussed include Electrical Discharge Machining (EDM), investment casting, Hot Isostatic Pressed Powder Metal (HIP'd PM), and Direct Metal Laser Sintering (DMLS).

INTRODUCTION

A customer of the authors' company once stated "show us your bleeding edge designs, but first show us an experience list with at least 5 other running installations." While at first reaction, the statement is rather humorous, it does speak volumes about the turbomachinery industry. In general, the industry is very conservative, but there is an element that exists that is also always looking towards the future. It's hard to place blame for that when the amount of risk involved in operating turbomachinery and the potential rewards are considered. Partly as a result of the conservatism, those who were present during the infancy of the centrifugal compressor would have no problem recognizing a modern compressor. It's a far cry, for example, from comparing an early telephone and today's smartphones, since at a high level, not much has changed in the compressor. If you look under the hood, it's a different story. OEMs have done a fair job through the years keeping abreast of current technologies and have incorporated it into the design and manufacturing of the equipment, despite the conservatism. This paper looks briefly at the evolution of the manufacturing methods traditionally used to make closed impellers before discussing newer, alternative methods for making small impellers as single pieces.

TRADITIONAL CONSTRUCTION METHODS

Three Piece

Three piece construction, so called due to the hub, blades, and cover being separate pieces, is most traditional of the three methods. The majority of the impellers made before the new millennium were made in this fashion. This method has several advantages. The multiple pieces and relatively simple designs of the day allowed for easy forming of blades, machining, and fabricating. Low alloy steels, such as 4100 and 4300 series steels, were commonly used and the thin sections allowed them to be through hardened. The thin sections also allow for a variety of product forms to be used, including plate, sheet, forgings, bar, etc. To fabricate the impeller, each individual blade was hot formed or machined to shape, the hub and cover pieces were machined, the blades were fit, and then the pieces were joined. The most commonly used joining methods for these impellers are riveting (Figure 1a) and welding (Figure 1b). While making all of the pieces separate allows for the advantages above, it also results in this method being very manual and extremely dependent on the skill of the workers. For example, misshaped or poorly located blades could have serious implications with respect to aero performance, modal behavior, and structural integrity. Fortunately, the less sophisticated designs of the day were very robust and operational requirements were less severe, which more than made up for the human factor and basically allowed this construction method to work well for decades.

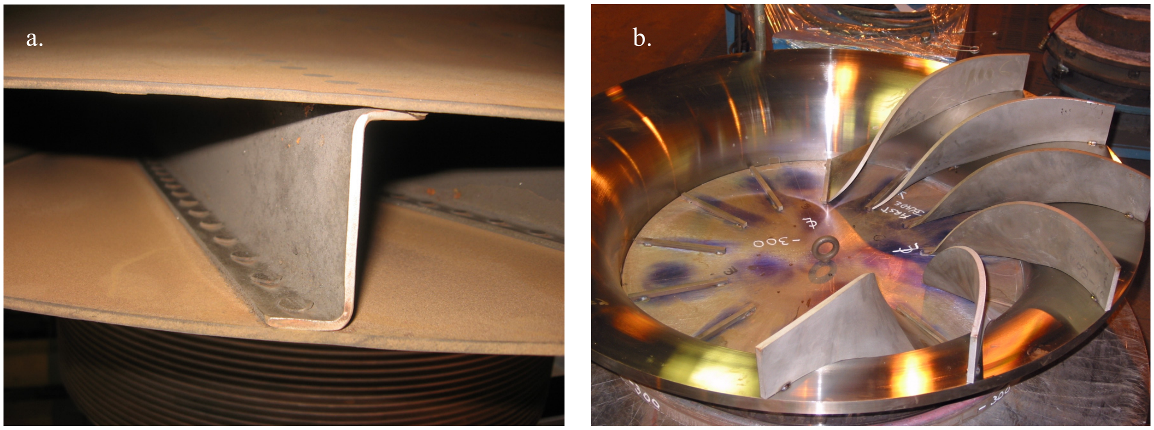

Figure 1. An example of three piece impellers, including a riveted impeller (a.) and a welded impeller being fit (b.)

Two Piece

Starting in the latter part of the 1990's, more complicated three dimensional impeller designs were being introduced and became more common place. This essentially spelled the end of three piece construction, because these designs had substantially less room for error to achieve a quality part. Due to this, OEMs moved towards the so called "two-piece" construction and most impellers made today use this method. As the name suggests, this type of construction uses separate hub and cover pieces with the blades integrally machined into one of the halves. The pieces are almost exclusively forgings. With the availability of 5 axis CNC milling, complex blade designs are able to be accurately machined to tight tolerances. Being computer controlled the variability within and between impellers is greatly reduced by removing much of the possible deviations. The impeller halves are typically joined by fillet welding (Figure 2a), slot welding (Figure 2b), brazing (Figure 2c), or a combination of these methods. Much of joining is performed, at least in part, manually. Even cases where robots or other automated methods are utilized, the impeller is typically manually tack welded together beforehand. Unfortunately, all of these joining processes require heat and can result in distortion, which can negate some of the gain from integrally machining the blades. Despite these faults, the two piece method has been very successful and allowed for great strides in performance and reliability. In fact, Lüdtke (Lüdtke 2004) described 5 axis CNC milled and welded or brazed impellers as "… the highest quality as far as precision, strength, material integrity, and erosion and corrosion resistance are concerned".

Figure 2. Examples of two piece impellers, including an impeller prepped for fillet welding (a.), a slot welded impeller in a fixture (b.), and an impeller brazed using foil and paste

One Piece

When considering where to go to improve upon the two piece method, it stands to reason that if two pieces is better than three, then one piece must be better than two. It must be sound logic, as that is the direction that the industry appears to be taking. One piece construction, as the name suggests, consists of a single piece of metal with no joints. Given the stigma that welds "are a necessary evil that should be considered defects between two perfectly good pieces of metal" (Dowson, P. personal communication, 2009), it's not difficult to justify appeal of one piece construction. This is not a new idea to the industry, as cast impellers are not unheard of, particularly in the pump industry, but it is being revisited with modern manufacturing techniques that make it more cost effective. From the OEM perspective, the one piece impeller is about as close as possible to the design, since the removal of all joints virtually eliminates any manual processing and associated defects. Given this, from the user perspective, if the compressor is operated correctly, the impeller should ideally run indefinitely. Being essentially a win –win situation, one piece construction is gaining in popularity and is beginning to be expected as a standard offering by some users and EPC's (Ross, S. personal communication, 2014).

With the experience most OEMs have with 5 axis machining of two piece impellers, it's a natural progression to utilize that process to make a one piece impeller. Figure 3 is an example of a one piece impeller machined using a 5 axis mill. Similar to the two piece method, forged material is used. Obviously in this case, a single forging is used that is slightly larger than the halves used in two piece construction to accommodate the entire impeller. The articulation of the 5-axis machines allows for most flow path profiles to be machined, and impellers of any size are theoretically possible. The extent to which a design can be machined depends on the accessibility and the reach. Relative to accessibility, the tools have to be of a small enough size to fit into the flow path and have line of sight to machine the profile. Tool size is a major limitation with respect to small impellers. Reach is an important consideration, since the larger the impeller, the longer the supports must be to hold the tools. As the flow path height decreases, the tool size and the size of the supports must also decrease. With larger impellers with small tip openings, the long, thin supports are often not rigid enough to prevent deflection or tool bouncing, which can damage both the impeller and the tool. Small impellers with tight tip openings essentially have two strikes against them, with typical tools being too large and extremely thin supports required if the tools were available. Due to these factors, most one piece impellers currently encountered are large, and relatively open designs. Milled one piece impellers, as well as two piece impellers, are also very wasteful. In some cases, upwards of 75% of the forging may be turned into chips. This could, in theory, limit the possible materials to make the impellers from. As an example, it would be a struggle to make a titanium impeller cost effective given the high raw material costs, increased difficulty in machining and the amount of waste resulting from manufacturing.

Figure 3. One piece machined impeller

ALTERNATIVE METHODS

It is clear that before the industry can move solely to one piece impellers, some gaps will need to be filled. When making a plan of attack, the low hanging fruit of large size, large opening impellers are very well covered by 5-axis milling, although it remains to be seen if that is the overall best method. It makes sense then to attack from that position of strength to find where its limits lie. The authors company and probably most OEMs, have done that and have a fairly good feel for what 5 axis milling is capable of. The question then becomes how one attacks the other end of the spectrum?

The remainder of this paper discusses four alternative manufacturing methods that the authors company is investigating as options capable of addressing the small impeller, small tip opening end of the spectrum. The specific processes being evaluated are EDM, Investment Casting, HIP'd PM, and additive manufacturing. For the initial investigations, suppliers were contacted and given the same impeller design shown in Figure 4 to evaluate and quote. The impeller is roughly 300 mm diameter, has 3 dimensional blades, and a tip opening less than 6 mm. The tolerances on the drawings were 5-axis milling tolerances for two piece construction, although it was understood that the tolerances are not likely possible for most of the processes. 17-4 PH in the NACE MR0175 (2009) compliant 1150ºF double aged condition was selected as the material of construction, although for reasons explained later, the additive manufactured impeller was changed to Inconel 718. Due to the custom designed nature of impellers, rapid prototyping and similar concepts were incorporated to reduce costs and lead time associated with permanent tooling. The impellers were subjected to a battery of tests to evaluate the dimensional accuracy and structural integrity, as well as to characterize the resulting material properties. Each process will be discussed in detail separately. The results of the tests will then be summarized and each process will be ranked with considerations to cost and delivery, manufacturability, and suitability for service.

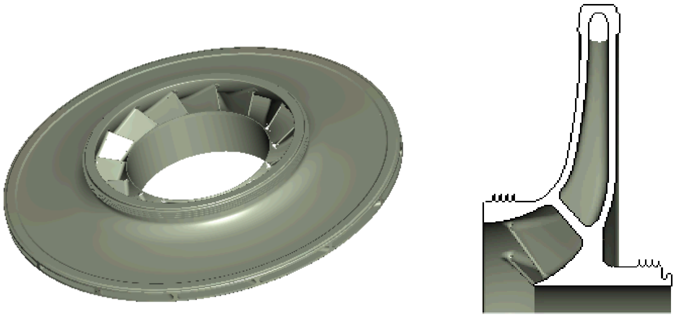

Figure 4. Model of the selected impeller for the project

EDM

Electrical Discharge Machining or EDM is the process of removing material using a series of electric sparks. While the observation of the damage from lightning strikes has been observed since the beginning of human kind, it wasn't until 1770 that the spark erosion phenomenon was characterized by English scientist Joseph Priestly (Webzell 2001). It was not until the 1940's that Russian researcher Lazerenko developed a power supply that paved the way for the phenomenon to be harnessed for controlled material removal (Anonymous 1965). It was initially relegated to the useful, but lowly task of being used to remove broken drill bits from holes (Webzell 2001). Since that time, EDM has developed to the point that it has become the most popular of the unconventional machining methods.

As stated above, EDM is an unconventional machining process. Jameson (2001) provides an in depth discussion on the various aspects of EDM, some of which are summarized below. Conventional machining is a mechanical process where a tool physically touches the part and cuts material away. In EDM, the tool is an electrode and it is separated from the part a certain distance, known as the spark gap. Figure 5 illustrates the EDM process. Dielectric fluid is flowed in the gap. The dielectric fluid is an electrical insulator under normal conditions. When the voltage applied to the electrode exceeds a critical value, ionization of the fluid occurs and it changes to an electrical conductor. When this change occurs, a spark is discharged at the location of the shortest distance between the tool and the part. Sparks occur at about 2,000 to 500,000 times a second and never at the same location. The temperature at either end of the spark is extremely high and actually vaporizes a small amount of material from both the electrode and the part. The vapor rapidly solidifies as a chip and the flowing dielectric fluid washes it away. The local nature of the sparks and the rapid cooling of the dielectric fluid keep the overall part cool to the touch, but there are remelted areas that remain on the surface. EDM is considered to be a thermal machining process. In fact the only major issue with EDM is that it does leave patches of remelted material on the surface. This material is usually very hard and brittle due to the extremely rapid cooling rate and is very prone to cracking. Typically parameters are set to minimize the remelted or recast layer and often surface treatments are performed to remove the affected material. Control of the process keeps the "cut" width narrow and highly accurate when the tool is attached to proper CNC equipment. EDM does require the material be electrically conductive, but beyond that, the process does not necessarily "care" what the material is, which makes it useful for machining very hard materials that may not be possible to machine using conventional methods.

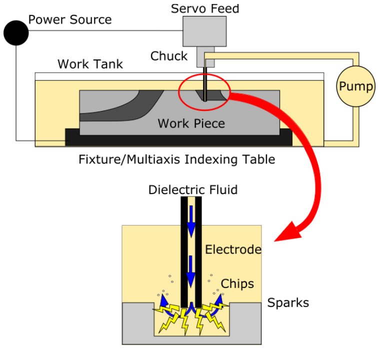

Figure 5. Schematic of the sinker EDM process

There are two main types of EDM processes, namely wire EDM and sinker EDM. Wire EDM can be thought of being similar to a scroll or jig saw. Although it is capable of more, the most simple and common application would be cutting shapes out of sheet and plate. Basically the work piece must be thin enough that the wire can be passed through the thickness and must be started at an edge or in a through thickness hole. Sinker EDM can be very complicated depending on application, but in its most simple form is analogous to using a drill to drill a series of holes into the work piece. By varying the location and angle of the tool and the depth the tool is sunk into the part, very intricate features can be machined. The complication arises from the design of shaped electrodes to more efficiently remove the desired material. Given the curvature and overall distance of the flow path in an impeller, sinker EDM is the process required to machine an impeller.

The process to manufacture the selected impeller via EDM is not drastically different than that for machining the impeller using conventional methods. Two disk forgings of fully heat treated 17-4PH were sent to the supplier. The supplier performed a pre-turning operation to roughly shape the OD and hub and cover contours. The flow paths were then machined on a sinker EDM machine. After the flow paths were in place, the impellers were turned to final dimensions and dimensionally inspected. One of the forgings only had a total of four of the 15 flow paths machined, two adjacent flow paths separated by 180 degrees from the other two. One set of flow paths was left as machined to evaluate the recast layer. As mentioned above, the recast layer is commonly thought to be very detrimental, although in recent years, machine shops have been able to achieve very thin and discontinuous layers that could possibly be left as is. It is also important to understand what could be the worst case scenario if the removal process fails. The other set was abrasive flow machined to remove the recast layer. Abrasive flow machining is the process of forcing an abrasive laden high viscosity material through the part. The abrasive grinds the surface and can achieve a very fine, mirror like finish. The other forging was machined as the full impeller and was also abrasive flow machined. The full impeller (Figure 6) and sample (Figure 7) were returned and the remaining processing and testing was performed in house.

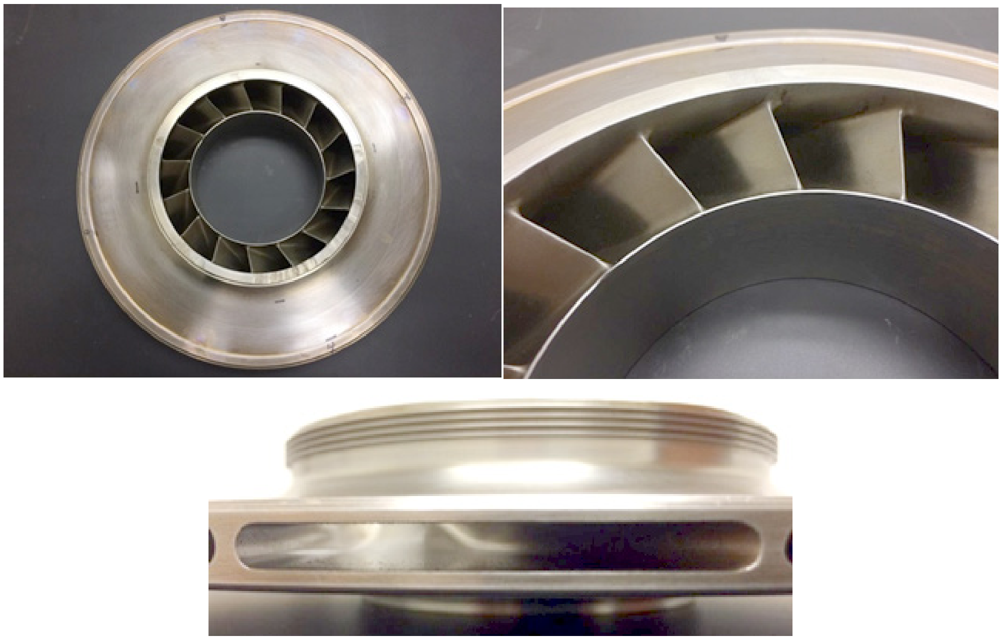

Figure 6. Images showing the EDM’d full impeller

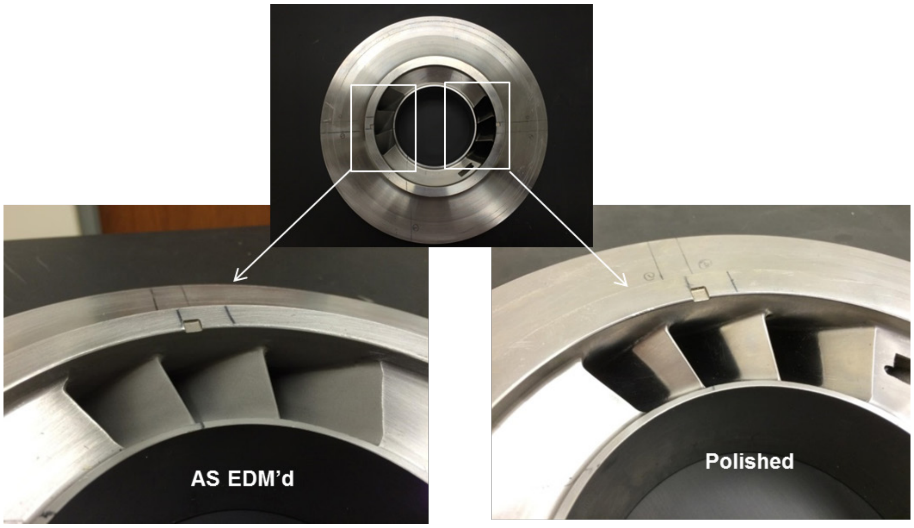

Figure 7. Images of the sample piece

The sample was cross sectioned in both the as EDM'd and abrasive flow finished flow paths. The presence and thickness of the recast layer was measured in each area. In the as EDM'd surface, the recast layer is approximately 10 µm thick and is very spotty. Cross sections were taken and the length of each recast island was measured and divided by the total length of surface. The recast layer accounted for 9% of the flow path surface of the cross section on the as EDM'd surface. Figure 8 shows the approximate locations of recast layer islands in red. Interestingly, the recast layer is not visible near the eye (inlet) of the impeller. Also shown in Figure 8 is a representative cross section of the islands. The same process was repeated for the abrasive flow machined surfaces. The process did not entirely remove the recast layer islands, as seen in Figure 9, but it did reduce the amount to 2%. The thickness of the islands also seems to have been reduced in many cases, but there are still instances of islands that are ~10µm thick. If EDM is to be used for impellers, further work may be required to determine if the remaining recast islands are likely to be an issue or revisit the processing to remove it entirely.

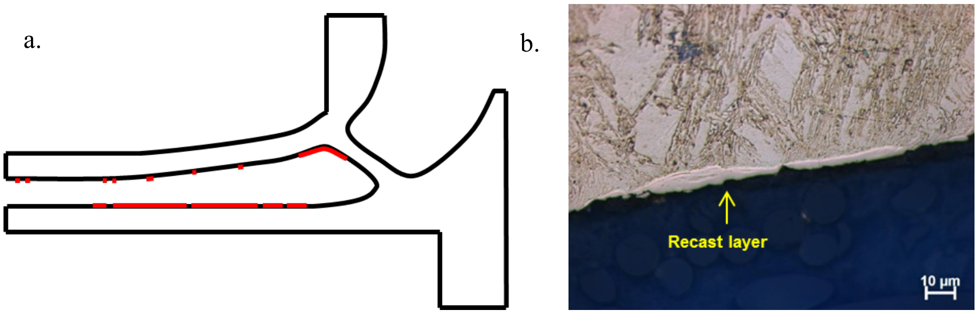

Figure 8. Schematic of the impeller flow path showing instances of recast layer (red) (a.) and cross sectional image of a typical island of recast material on the surface (b.) in the as EDM'd passages

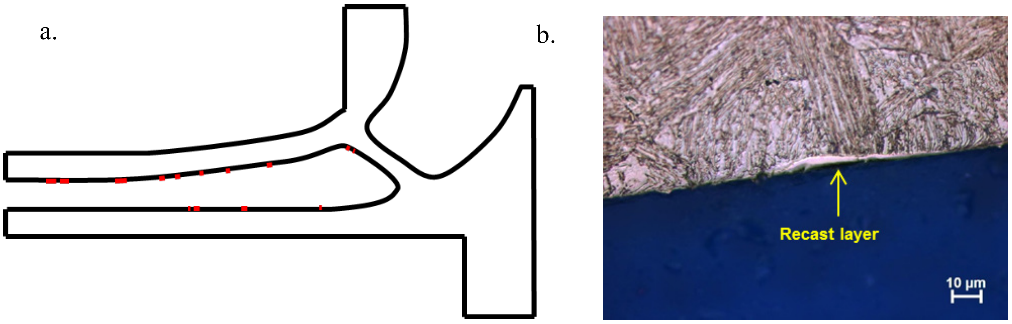

Figure 9. Schematic of the impeller flow path showing instances of recast layer (red) (a.) and cross sectional image of a typical island of recast material on the surface (b.) after abrasive flow machining

The full impeller was treated as a typical production impeller would be in the shop. The impeller was magnetic particle inspected. As would be expected on a single piece of forged material, there were no indications found. Being that the forging was already heat treated, the properties did not change from the certification from the forging supplier it was not necessary to retest for material properties. It was dimensionally inspected and found to be within the same tolerances as specific for a 5 axis milled two piece impeller. One slight deviation from typical processing was that the impeller was spin tested at the maximum rated speed rather than a speed based on a specific job requirement. Given that 17-4PH exhibits significant continuous yielding behavior it is actually spin tested twice. The reason for this is that the limit of proportionality or the elastic region where it behaves linearly on a stress strain curve is very small in this type of material. The material is essentially always yielding, resulting in permanent deformation, as shown as the loading line in Figure 15. Once the deformation occurs, the material thereafter behaves linearly at stresses below the maximum and assuming the maximum stress is in the elastic region, no further permanent deformation occurs at lower stresses (unloading/reloading line in Figure 10). Based on this, 17-4 PH impellers are spin tested the first time and allowed to deform or grow to increase the limit of proportionality. Then they are machined to the final dimensions and spin tested again to ensure no further growth occurred. The impeller survived the first spin and showed typical amounts of growth on the subsequent dimensional inspection. It was then finish machined and spin tested again. Only one dimension was found to be out of specification after the second spin. The distance from the back of the hub to the end of the bore was slightly out of tolerance. This was reported to be due to a tool break during machining prior to the second spin.

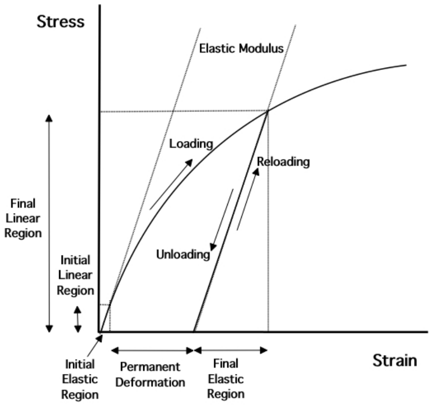

Figure 10. Schematic illustrating the stress-strain behavior of continuously yielding materials

It was mentioned above that one piece impellers should be the closest to achieving the ideal cases of the actual design. To perform a high level check on that theory, the impeller was rap tested (Pechulis 2015). Comparing to finite element analysis (FEA) results, the second nodal diameter was 6.5% lower than predicted while nodal diameters 3-7 averaged 2.2% higher than predicted. The mean blade leading edge frequency was 9-15% higher than the predicted frequencies. The standard deviation between the blades frequencies was 0.17%. This shows very little deviation between the blades, although the amount of mistuning that this represents is within the range that the authors company has measured on several recently tested 2 piece impellers (Braman 2017).

The final check on the impeller was an in-depth dimensional check. The outer surfaces were measured using a structured light process. The impeller was then be cut apart using a well-defined wire EDM process. The internal surfaces were measured using the structured light process. All of the measurements were then be reconstructed and compared against the model to evaluate the overall and more importantly, the flow path accuracy. Of particular interest was the transition area on the cover, where it may be difficult to reach via EDM. Unfortunately, the impeller had residual stress in it, most likely from the spin tests, and sprung a large amount when it was cut apart. Very limited data was able to be gleaned from measurements when compared to the model.

Being that EDM is a mature machining method, it is the easiest of the processes evaluated to implement. Based on that, the supplier was sent several designs to evaluate for compatibility with the EDM process. Surprisingly, the complicated, 3 dimensional designs which are difficult to manufacture as two pieces were said to be easy for this process. The problematic designs were the simple, 2 dimensional designs with small flow path openings and nearly 90° transition in the flow path. The reason for this can be explained by considering the drill analogy for sinker EDM. Drill bits do not bend, and as such, line of sight is required to machine the flow path. As illustrated in first schematic in Figure 16, the geometry results in an area on the cover side in the transition that is not able to be reached. To be able to reach this area, the bore at the eye of the impeller would need to be cut back, as shown in the "modified" schematic in Figure 11. In these instances, an evaluation would be required to determine if enough contact surface remains to prevent movement of the impeller on the shaft prior to making any changes.

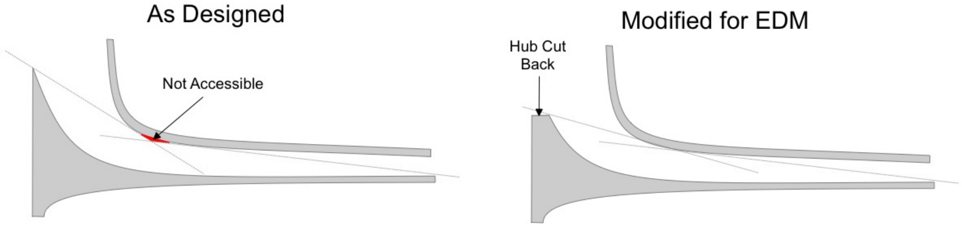

Figure 11. Schematic showing an example of an area inaccessible via EDM and the required modification

Investment Casting

Investment or lost wax casting is by far the oldest of the methods considered in this work. Archeologists have recovered artifacts dating to ~3500BC that are believed to have been investment cast (Hunt 1980). Some of these artifacts have complex forms and intricate details that would be virtually impossible to make any other way given the tools available (Hunt 1980). The advantage of investment casting lies in the way the mold was created. Initially the actual part that is desired is made from wax. Wax is obviously easy to form with smooth surfaces and high detail using even primitive tools. The wax was then coated with a slurry containing clay. The composite structure could then be treated essentially as pottery, being heated to melt and remove the wax and to fire the clay. The result was a strong mold. Molten metal, initially smelted copper (Hunt 1980), was poured into the mold. When the metal cooled, the mold was broken off, leaving a metal part with all the detail of the wax pattern.

Through the years the basic concept has changed little, but the process has been optimized for mass production. Figure 12 shows a schematic of a modern investment casting process. Rather than hand working the wax, permanent dies are typically used to injection mold the wax to shape. The wax pieces are attached to preform gating pieces to form pathways for the molten metal to be fed to the casting. The gates also can be used to make trees of several patterns, allowing molten metal to be fed to several molds simultaneously. Very fine slurries/stuccos are used in the investing process to build the initial layers of the mold to perfectly replicate the detail of the wax pattern. Coarser slurries/stuccos are used to build the outer layers rapidly and with increased strength. Most foundries have some sort of automated system for holding the trees and applying the ceramic. Alloys that are investment cast range from simple copper to some of the most complex nickel based superalloys. Additional features have also been added. For example, chills and grain selectors are built into the molds to give a certain grain orientation or single crystal materials that are used in high temperature applications. It is astonishing to consider the critical technological applications, such as gas turbine blades and medical implants, which investment casting is frequently used for given the ancient origins of the process.

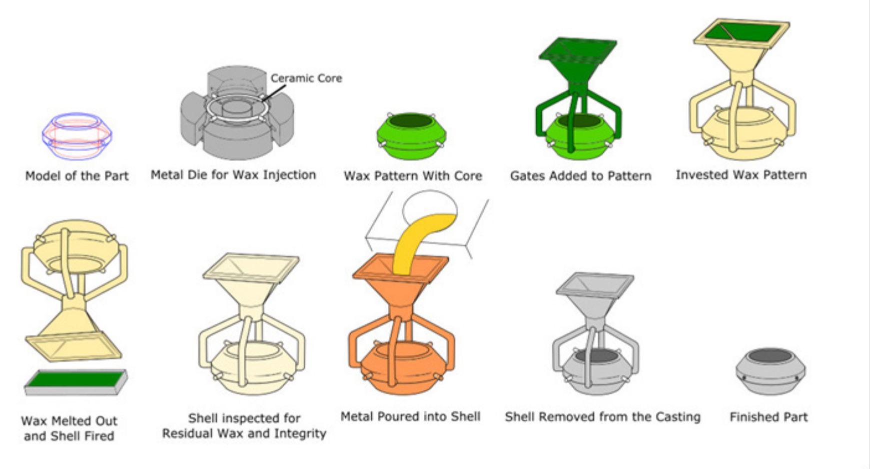

Figure 12. Schematic of the traditional investment casting process

As mentioned above, investment casting is not new to rotating equipment or even more specifically to impellers. An internet search for investment casting foundries will find a large percentage of web sites for foundries with pictures showing examples of cast open and closed impellers. In fact; the authors' company manufactured closed centrifugal compressor impellers in the early 80's using investment casting. These impellers met all of the mechanical and dimensional requirements at the time. The per part cost was reasonable and the lead time was good. Unfortunately in this application, the greatest strength of investment casting is also the source of its weakness. Conventional investment casting requires a die or tool to make highly repeatable wax patterns in a very short period of time. There is a significant upfront capital cost for the tooling and severe hit to the lead time to design and manufacture the tooling. Although the process can produce parts rapidly and relatively inexpensively once the tool is available, a number of parts are frequently required to offset the initial commitment. The process was cost effective when impeller designs were reused regularly. As new design methodologies and computers became more prevalent, it became easier to make minor tweaks to optimize designs for specific applications. In fact, other than for spares or replacement on a given compressor, the author's company rarely, if ever, uses the exact same impeller again. Each change would require either a new tool or a permanent change to an existing one when the parts that are being made are one-off. Adjustable tooling may work in some circumstances, but is limited in the number and extent of ways the design may change. Obviously the costs and lead times skyrocket in that situation and investment casting loses its competitive edge.

In recent years, the investment casting industry has been widening its net to capture specialized one off applications. This is being accomplished by incorporating additive manufacturing (aka rapid prototyping or 3-D printing) techniques into the pattern making process. While wax based printers are available, they are not currently in widespread usage, nor do they currently have large build dimensions (currently about the size of a sheet of paper in the horizontal plane). As these machines are being developed, machines that work in various polymers are filling the void. In fact many machines and materials used for the rapid prototyping in polymer materials are specifically designed for use as investment casting patterns. The rapid prototyped plastic materials are able to achieve a high amount of detail and surface smoothness. Some processes even impregnate the surface of the plastic with wax to further improve the surface finish such that they can rival fully wax patterns. As an example, Figure 13 shows a pattern of an impeller printed using the QuickCast process. The process uses a photoreactive polymer resin and prints bulk portions of the pattern as a honeycomb structure to reduce weight. The honeycomb also allows the pattern to collapse in on itself when heated to burn it out. These patterns are able to be coated with the ceramic slurry, so there are little to no changes required for the investing process. The major difference is in the pattern removal. The plastics are generally burned out rather than melted and poured. It is therefore important to consider thermal expansion of the plastic, so it doesn't break the low expansion mold materials. Other considerations are venting of the gaseous products generated by the burn out and the amount and removal of any residual ash. After the pattern is removed, the remainder of the processing is unchanged.

Figure 13. Photo of a QuickCast pattern of a double flow pump impeller

Given that investment casting was successfully used for impellers in the past and rapid prototyping appears to overcome the reasons why it fell from favor, investment casting was explored as a possible method to make the test impeller. Several foundries were contacted before selecting one to work with. The common consensus from all the foundries was that while impellers are commonly made, this particular impeller would be pushing the limits of the process. Impellers typically investment cast that have the same number of blades and of a similar shape are almost exclusively open impellers. Most closed impellers that are cast are pump impellers, which tend to have fewer, heavier blades and more open flow paths. This impeller is closed with 15 thin blades and very tight tolerance requirements. Investment foundries often quote +/-5 to +/-10 μm/mm as a standard on dimensional tolerances. Premium quality castings frequently achieve better than that with traditional wax patterns, but the use of rapid prototype patterns adds to the variability. The desired tolerances on this impeller are essentially machining tolerances, which competing processes, such as EDM are capable of. The narrow flow passages in the impeller are also a source of difficulty. Passages in the size range of those in this impeller and smaller are problematic to invest properly. The ceramic slurry tends to bridge and can close off part of the passage before adequate thickness of ceramic is achieved. The thin, weak areas of the mold can rupture during casting. This obviously ruins the part, but also presents a safety risk to the foundry workers. The fact that an impeller is designed to move fluids through it is advantageous for this method. Despite the risks, a few foundries believed that with care in the investing process, even to the point of manually dipping the impeller, the flow paths could be properly filled. The relatively large masses of the hub and cover are connected by the thin blades also complicates the matter. Depending on the pattern and gating designs, one of these large masses may be required to be fed molten metal through the blades. If care is not taken, the thin blades may solidify before the mold is filled. Since this is the most cost effective method to investment cast this impeller, an impeller was made using this method.

While it was not an entirely smooth process, the impeller was successfully cast into metal using the invested flow path method. The mold was highly scrutinized prior to casting and found to be very sound, particularly in the flow paths. Unfortunately, there was a mishap during casting and the bottom of the mold broke before the metal solidified. This is a known risk with the investment casting process. Given that the failure was not related to the investing of the flow path, a new pattern was quickly made and the process restarted. The pattern was invested and the mold was inspected. The mold was well formed and clean, so it was moved to casting. The support for the mold was made more robust than the previous attempt. Overall the foundry reported the casting process went very well. Figure

14 shows the impeller after the gating was removed. Visually, the flow path and blades were very well formed. The surface finish in the flow path was excellent. Based on that, the impeller was moved to HIPing and heat treating to finish the processing. The impeller had one small blemish on a blade that was weld repaired. Beyond that, the casting passed the NDE requirements. With respect to the dimensional accuracy, the results were a mixed bag. Structured light scans were used for the dimensional analysis and the impeller was EDM cut to facilitate the process. The hub and cover profiles (Figure 15) were found to be well out of tolerance and somewhat variable. The tip openings (exhaust) were oversized and out of specification, but showed some consistency. Surprisingly, given the other deviations, the blade shapes were actually fairly good (Figure 16). The majority of the scanned points fell within the required profile tolerances, but the overall deviation was slightly out of specification. These points were well within what the foundry expected to achieve. The samples that were processed along with the impeller were tensile tested and impact tested. Table 1 shows the comparison of mechanical properties of the casting and the spec requirements. As can be seen, the yield strength is slightly higher than 120 ksi. The hardness was within range, which means the impeller would be acceptable for NACE applications as is, but would require re-aging to bring the yield strength down to be acceptable for hydrogen service. This is not uncommon in standard impellers. The impact properties were very close to the spec minimum at room temperature. An internal specification requires testing at -100^{o}F, but the results shown in Table 1 at -50^{o}F are already below the required value. This means that this particular impeller would not likely be acceptable for low temperature.

Table 1. Mechanical properties of investment cast specimens

	Yield Strength (ksi)	Tensile Strength (ksi)	% Elongation	% Reduction of Area	Hardness (BHN)	Impact Energy @-20F (ft-lbs)	Impact Energy @ -50F (ft-lbs)
1	127	141	17	51	294	15.1	11.2
2	127	141	19	57	319	15.2	11.8
Specification	100-120	120 min	11 min	30 min	250-331	*	*

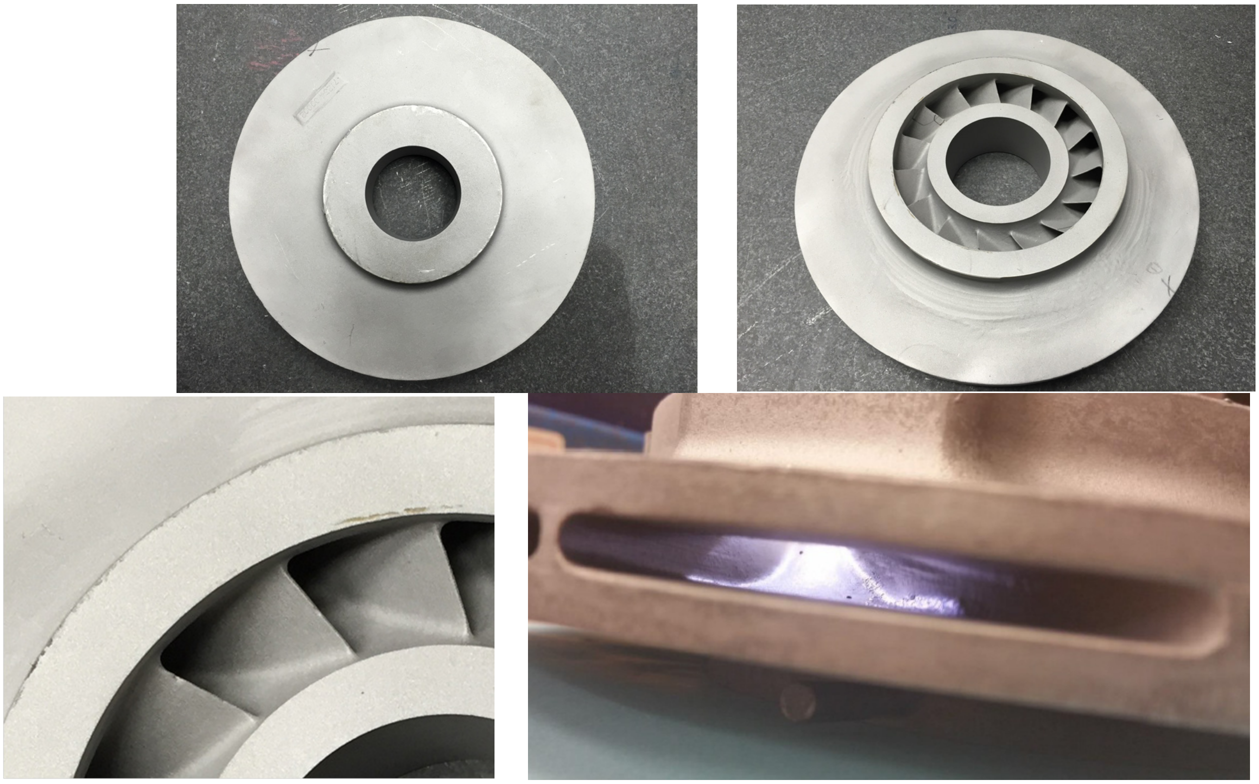

Figure 14. Investment cast impeller after gate removal

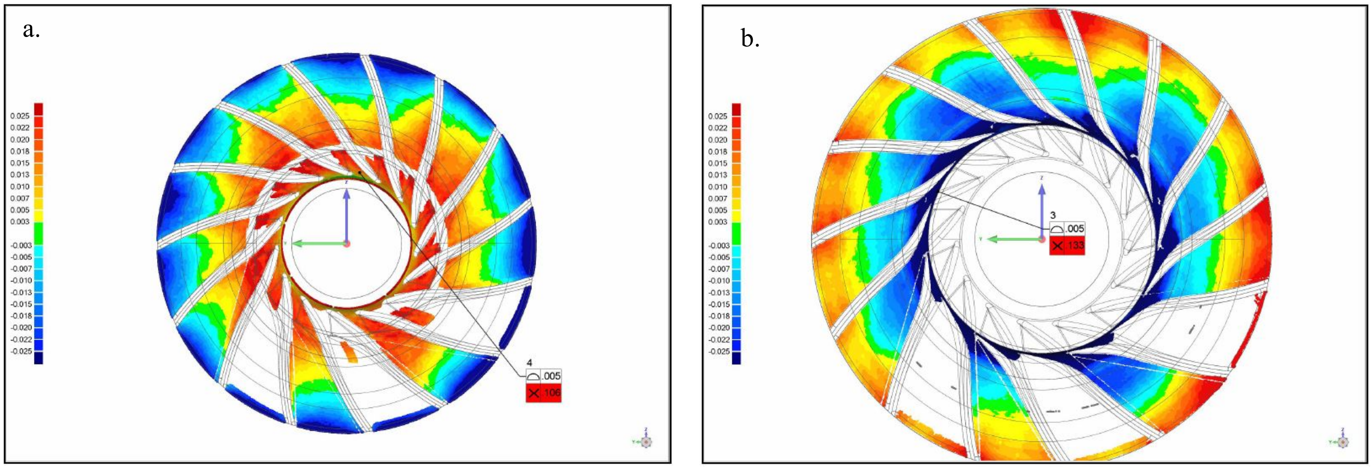

Figure 15. Color maps showing the deviations from the model for the hub (top) and cover (bottom)

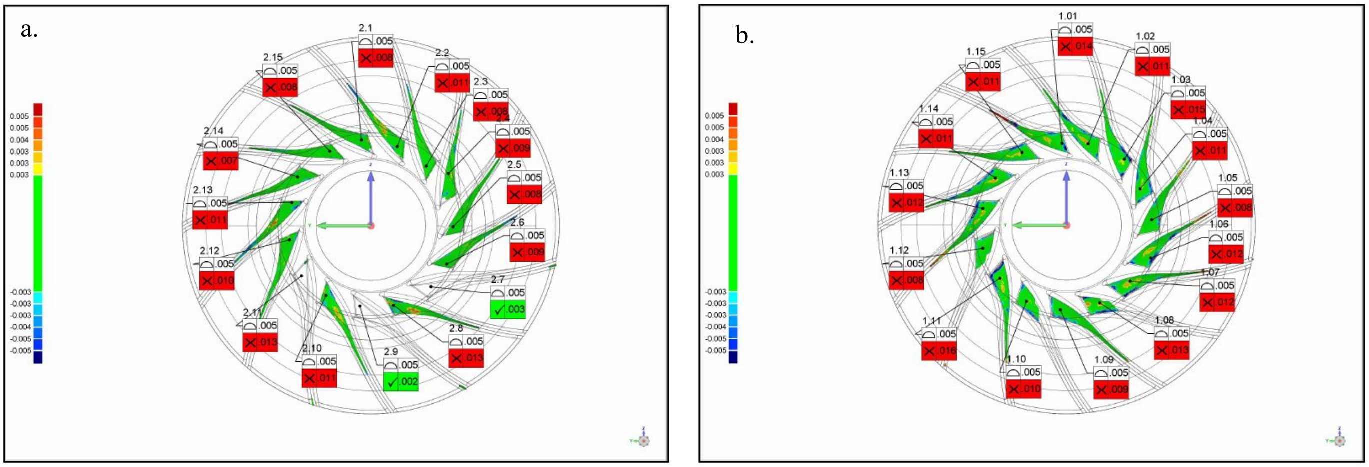

Figure 16. Color map showing the deviations from the model for the pressure side (top) and suction side (bottom) of the impeller blades

There are expected to be limits to how small of any opening can be to allow proper investing. Other methods were also considered with this possible issue in mind. To get around the problems with investing small passages, solid ceramic cores in the shape of the passage are often incorporated into the pattern and designed to remain in the mold after burn out. In the case of an impeller, the core would be the negative of the flow path. For mass produced parts, the cores are made with permanent tooling similar to the wax patterns, which is obviously not desirable for this application. Once again, rapid prototyping, this time of ceramic materials, was investigated. Similar to wax, processing ceramics in this manner is not nearly as mature as plastics or even metals and machines large enough to make a core for this impeller were not readily available at the time. To evaluate the feasibility of using a ceramic core, a two piece core was made. One source of possible problems with using a printed ceramic core is that ceramics differ from metals and polymers in that they are not melted in the printing process. They are loosely held together by a binder and then sintered, which is simple terms is heating to cause the particles to diffusion bond. The sintering process results in shrinkage and can introduce distortion. Prior to investing using the core (Figure 17a) it was dimensionally inspected to determine if it was accurate enough to be worth processing further. The tolerances were fairly large for the core, but they were close enough to have value to pursue further since the objective was to evaluate the process. To make the mold, hub and cover patterns (Figure 17b) would be made using the same plastic process used above. The pieces are then assembled and the assembly would be invested. The first impeller being made with this process suffered the same fate as the first invested flow path impeller. The replacement core had slightly better tolerances, but it had broken in shipping to the foundry. Since the coefficient of thermal expansion of the core material and the stucco mold are very similar, it was decided that the pieces could be fit back together manually and once the pattern was invested, the core would be locked in place. It appeared that this was the case after the investing process.

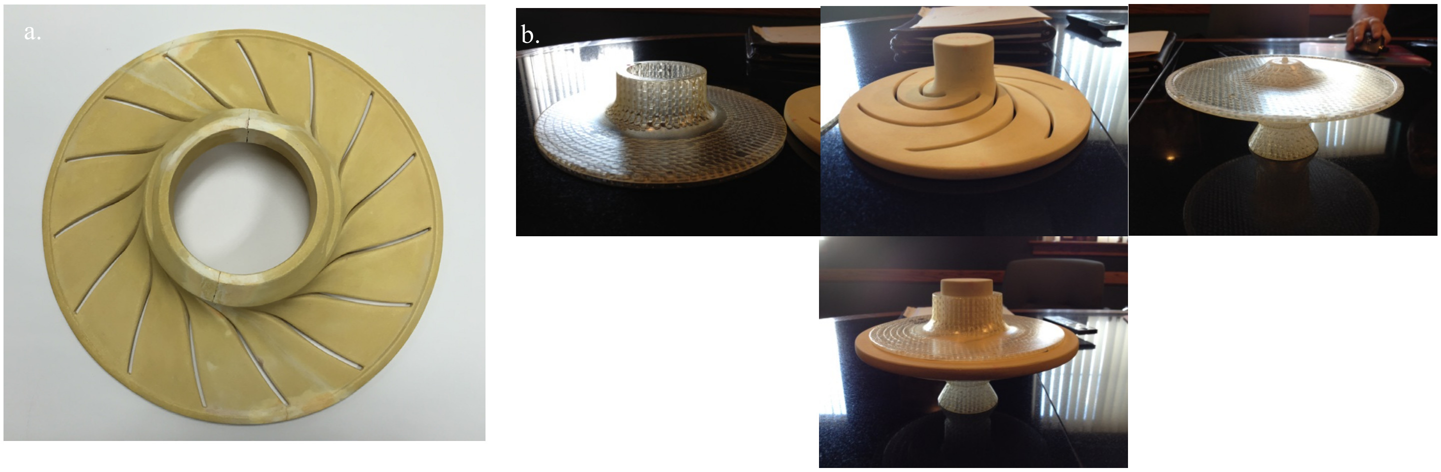

Figure 17. Ceramic core of the reverse of the impeller flow path (a.) and an example of a core with printed patterns (b.)

The resulting casting had a bevy of issues. Despite the appearance of a well fitted and locked in core, the core shifted at some point and the impeller exhausts were not in the same plane around the OD. The leading edge of the blades did not fill well, leaving large areas with missing metal. This is a possible indicator that the mold/core was not hot enough when the casting was poured or cooled too rapidly during. There was also significant burn in where the molten metal penetrates into the core resulting in extremely poor surface finishes. Being that the core formed the flow path and the process was being used due to the fact the flow path is not accessible for machining to clean up, this is unacceptable. Given these issues and the overall poor adherence to the drawing tolerances, no further work was done to this impeller.

Hot Isostatic Pressed Powder Metal

For the purposes of this paper, powder metallurgy can be defined as the process of making solid components from powder precursors by the application of heat and pressure. Powder metallurgy can trace its origins back nearly as far as investment casting. There is evidence in India and from the Incas of direct reduction of iron ore with charcoal to produce sponge iron powders. These powders were subsequently formed into solids by forging. An example of this is the Ashoka Pillar of Dehli in India (Angelo 2008). Strangely, with great works being created using the process, it is believed to have been forgotten from that time until the 1800's when it was recorded to be used for producing platinum (Ramakrishnan 1983). The first major industrial use was in the early 1900's making tungsten filaments for light bulbs (Angelo 2008). The process really hit its stride in the 1955 with the invention of Hot Isostatic Pressing or HIP by researchers at Battelle (ASME 1985). Prior to this, pressure had to be applied in discrete directions. This led to inhomogeneity in terms of powder consolidation and some anisotropy in the material properties, which limited the complexity of the parts. HIP is performed in a pressure vessel with high pressure inert gases applying pressure uniformly over the surface. This addressed the downfalls of previous methods to apply the necessary pressure. Today powder metallurgy is a large industry and competes in some of the same high tech markets as investment casting.

Prior to the inception of the projects that are the subject of this paper, the authors company had worked on a powder metal impeller. Same as the work discussed here, the material selected was 17-4PH, but the impeller was larger with a more complex flow path contour. The first part of the process to make the impeller was to design the carbon steel can that would be used to contain the powder. The bottom piece of the can (grey in Figure 18a) was essentially dish shaped to accommodate the tail end of the bore, the back wall of the impeller and some of the flow path height. To reduce the amount of powder required, a 17-4PH forging was machined to serve as the bore and part of the back wall of the impeller. This is shown as the brown piece in Figure 18a. It was expected that this part would fuse with the powder to make a single part. Similar to what was discussed for the ceramic core for investment casting, the reverse of the flow path was machine out of carbon steel and placed in the can (pink in Figure 18a). The top of the can consisted of two pieces. The first was essentially a ring that made housed the remainder of the flow path height at the tip and the horizontal part of the outer cover surface (dark grey). The second part made up the vertical part of the cover and had the proper accommodations for purging and filling the can with powder (light grey). Figure 18b shows a cross section of the can. The blue in this figure indicate open areas to be filled with powder. After the can was properly filled with powder, it was evacuated, sealed, and finally HIP'd to sinter the powder. When the HIP cycle was completed, as much of the carbon steel can as possible was machined away. The part was then submerged in an acid tank to leach out the carbon steel flow path insert and any remaining carbon steel on the outer surfaces. At this point, the impeller was processes as any other 17-4PH impeller. The final impeller is shown in Figure 19.

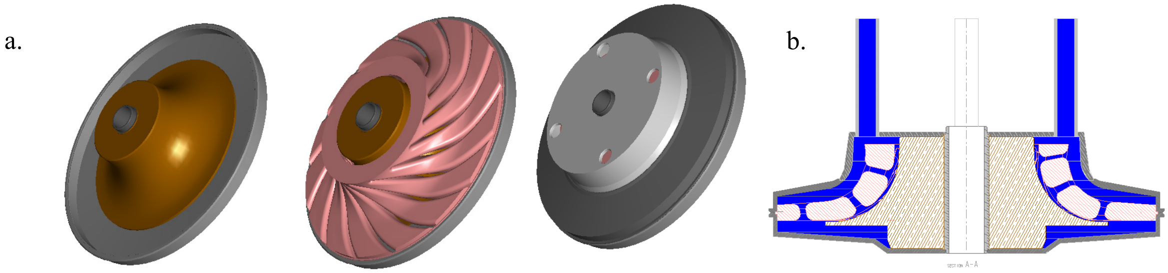

Figure 18. Model showing the can, bore piece, and insert for the powder process (a.) and a cross section of the assembled can (b.)

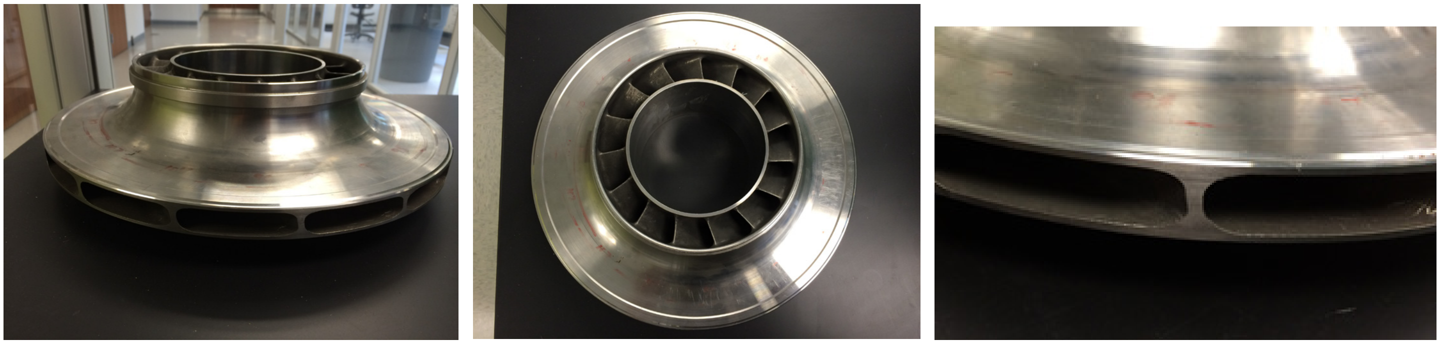

Figure 19. Photos of the final HIP'd PM impeller

The testing program was similar to what was done for the current project. The impeller passed NDT inspections and the mechanical properties were also acceptable. The impeller did not pass the dimensional inspection. All of the dimensions measured on the outer surfaces were acceptable. Measurement of the flow path contour showed that the vertical to horizontal transition region of the cover was incorrect and with the outer surface machined properly, the cover was thin in that area. The impeller was not able to be safely spin tested as a result. The root cause of the deviation was determined to be an error in a calculation by the vendor, which is not unusual in a first article in a new process. In this process, volume shrinkage due to sintering and thermal expansion are both occurring and are competing processes. The can design, and more specifically the insert design must properly account for both. In this case, the problem region was a transition where both processes are occurring significantly in multiple directions, which makes it a complex problem to work out.

In the time from that project to the current project, the vendor had gained more experience with impeller type parts and believed they had worked out the calculation problems. They found the impeller for this project less problematic in terms of the complexity. Unfortunately, the dimensional tolerances they quoted were very large, particularly given the small size of the impeller. The reason for this is once again related to the complex nature of the calculations. The typical process for developing a powder metal solution would be to do several iterations to optimize the calculations. This would then result in a rapid and highly repeatable process. Due to the fact that impellers are mostly custom designed for each job, it was not felt that this process is currently feasible for impellers and was not pursued further.

Additive Manufacturing

Additive manufacturing is a generic term that encompasses several processes that are used to create parts by adding material, which can be metal, plastic, or ceramic, rather than removing it as would be done in traditional machining (which is by extension a subtractive process). Most of these processes work by adding layers of material to build up a part, not unlike building with LEGO® blocks. In fact, from that perspective, one could argue that the basis for additive manufacturing has been known long ago in human history and great works like the Egyptian Pyramids are examples. Others do not have such a grand view of origins and trace the idea of using a layered approach to making complex shapes to the 1880's and the processes invented to make topography maps (Bourell 2009). With respect to additive manufacturing of metals, welders would argue that they have been doing it forever. In fact, in 1926, Baker patented a process of building three dimensional shapes with layers of molten metal using an electric arc as the heat source (Ding 2011). Fast forwarding to today, and there are several A/M processes available using metal. The basis of the vast majority of these systems is a weld process applying layers of metal, not unlike Bakers concept, although most are typically using powders and sophisticated positioning equipment for higher speed and precision.

There are two general types of metal additive manufacturing systems (Herderick, 2011). The first type can be thought of as free form welding, where layers of weld metal are deposited on a substrate and built up in space. The other types of systems are called powder bed systems, which is analogous to a stereo lithography type process. There are advantages and disadvantages to using these systems for an impeller application.

The free form welding systems are conceptually relatively simple. They basically consist of a welding head attached to positioning equipment (often a robot arm) that is integrated with additional positioning equipment for the part. There is a litany of advantages to these systems compared to the powder bed systems. The most significant advantage of the free form welding systems is that they are less limited in the build size than the currently available powder bed systems (Herderick 2011). The size is really only limited by the size/range of the positioning equipment being used or, if something like electron beam welding is being used, the size of the vacuum chamber or other containment available. These types of systems are very fast, with several weld processes that could be considered that can deposit material in the range of 10 kg/hr or faster (Ding 2011). There are a multitude of weld consumables available in virtually any weldable material, particularly for machines that use wire. This opens the doors with respect to material possibilities, because more materials are available, multiple materials could be used, and it allows for a variation of chemistry/properties throughout the part to optimize the final product. The positioning equipment also allows for some features, such as overhangs, be made without supports, which is a problem that will be discussed with the powder bed systems. Despite the numerous advantages, there appears to be fewer commercial options available and significantly less published work on these systems (Herderick 2011). Part of the reason for this is that in general, unless the part is extremely complex or is made from an exotic material, it is often less expensive to work with castings or in some cases, forgings. These machines also shine due to the build size and build rate. Unfortunately, these attributes are not normally conducive to high precision. In turn, the lower level of precision relative to the powder bed machines results in surface finishes that are not likely able to be used in the as printed state for most applications (Herderick 2011). Subsequent machining is required. Although the machining can be minimal relative to a forging or even a casting, it cuts into the time advantage and adds cost. This is obviously not acceptable for an impeller design where machine tools can not fit into the flow path after the part is printed. To address this, there are new hybrid systems becoming available that incorporate 5-axis machining into the system. Essentially these machines build a few layers with the additive process and then machine the surface and fine features as required before adding more material. Given the potential for impeller applications, plans are in place to include the hybrid processes in future evaluations.

Within powder bed systems, there are two types, those that use welding processes, such as laser or electron beam, and the so called binder jetting systems. Figure 20 shows the basic concept for these systems. The welding based systems, more commonly known as Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), or Electron Beam Melting (EBM), apply a thin layer of metal powder over a base plate. A high power laser or electron beam scans over the areas to be fused and melts the powder only in those locations (Herderick 2011). The machine lowers the base plate down and the machine applies another layer of powder on top and the process continues until the part is complete. The unfused powder is blown out and collected for reuse, leaving behind the printed part. The binder jetting systems are the closest to literally being a 3D printing process, as they use modified print heads to apply a binder resin to a powder bed similar to the laser powder bed system (ExOne 2014). This essentially glues the powder together rather than directly melting it. The "green" part is dried and the binder is burned out during furnace sintering. Currently, most parts made by this process are porous and must be back infiltrated by a lower melting point material such as a bronze. There are however, some materials that have been developed for near full density in small part sizes. It is not a far stretch to imagine that the binder jetting process would be hampered by the same complications as the powder metal process.

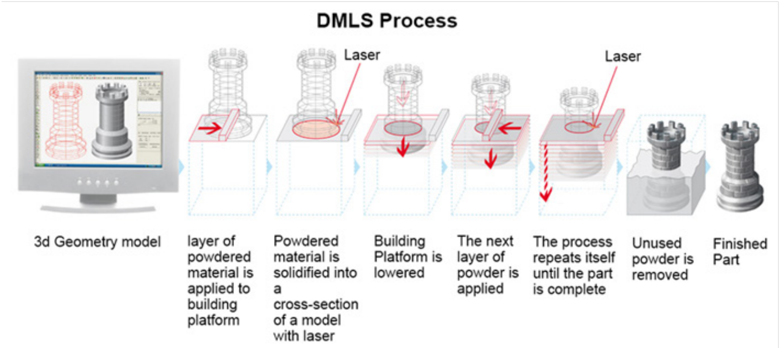

Figure 20. Schematic of the DMLS process (courtesy EOS)

Given the current deficiencies of the other systems, the DMLS process was chosen for this project. The timing was very fortunate. First, this project was in the early stages when Allison, et,al, (2014) reported on making closed impellers using DMLS as well, which helped this project move from lab curiosity to a process with a legitimate chance of success in the eyes of many at the authors' company. Secondly, machines with large enough build volumes to accommodate this impeller were only introduced to the market in mid 2014 and were just starting to become available to suppliers.

As with the other techniques discussed thus far, this impeller is not straight forward to manufacture using DMLS. The major issue with this design and closed impellers in general, is that as relatively flat rotating parts, it is preferred to be built horizontally. This minimizes the build height, which is a major contributor to the build time and in turn, the cost. Being dynamically loaded, it is important that the properties be as uniform a possible about the axis of rotation, which also favors a horizontal build. As a consequence of this, the faces of the hub and cover are nearly parallel to the base as the impeller is built. The process is currently only able to build surfaces like this for extremely short distances at an angle less than 25° from horizontal and it must be off of the build platform or a previous layer (Brancher, 2015). The powder bed by itself does not provide adequate support to build disconnected layers, as would be the case for example, for the start of the cover if built with the cover on top. Being essentially a weld, the residual stresses in the layer of solidified metal would tend cause it to curl up and be destroyed by the recoater blade when it applies the next layer of powder (Brancher 2015). To get around these issues in most additive machines, any surfaces less than 25° from the base require support structures be built into the part to essentially tether the layer to a previous layer or the base plate. This tethering allows the horizontal structures to be built. This is typical of this type of machine, even those that print in plastic. Figure 21 is a printed dental apparatus showing the as printed part with supports and the final part with the supports removed. While supports on the outer surfaces of the impeller can be machined off fairly easily, there is a significant distance in the flow path where the hub and cover are nearly parallel and requires supports. The yellow region in Figure 22 shows the extent of the supports required in the flow path of the subject impeller to build the cover. The supports typically are built with perforations, as shown in Figure 21, to make them as easy as possible to remove, but they are still metal and require tools to break off. Given the small tip opening, reaching all of the supports and removing any residual material may be difficult, if not impossible. In recent years, some work has gone in to redesigning supports and post processing steps, such as thermal deburring, improve the chances for clean removal.

Figure 21. As printed (left) and finished dental aparatus (courtesy EOS)

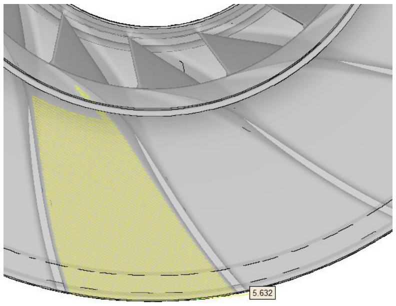

Figure 22. Schematic showing the extent of supports required in the flow path

A second consideration with the DMLS method is that of material selection. Most suppliers use powders provided by the manufacturer of the machine, as powders with the proper characteristics are just now becoming available elsewhere (Higgs 2015). In fact, some manufacturers require the use of only certain powders. It is also costly and time consuming to qualify new powders/materials and many suppliers to not have the expertise or resources. This limits the number of materials available to pick from. The options that could be used for impellers are 17-4 PH, 15-5PH, Inconel 625, Inconel 718, and Ti-6Al-4V (EOS 2014). All of these have some drawbacks.

At first glance, 17-4 and 15-5 PH, are obviously ideal choices since they are already are widely accepted in the industry. It is interesting that they are considered separate materials, as their chemistries largely overlap. The reason for the difference is in the way the powders are made. The 15-5 PH powder is atomized using argon gas. Parts printed with this powder are stated to be able to meet all the properties of wrought 15-5PH. The problem is that it is prone to cracking in highly restrained parts, as an impeller would be. Suppliers can and will build using this powder, but for a complicated part, it may be difficult to establish a robust process with a high probability of success, which will most likely increase costs. The 17-4PH powder is nitrogen atomized and the powder picks up a significant amount of nitrogen in the process (Murr 2012). Nitrogen is an austenite stabilizer and the parts made using this powder have a greatly increased amount of retained austenite as a result. This affects the properties of the material. In particular, the yield strength can drop as low as 80 ksi from the typical 100 ksi plus yield strengths expected from the NACE approved double 1150°F aging treatment. As an example of this, Allison (2014) reported on an attempt to make a 17-4PH impeller using similar equipment. They stated that impeller cracked on liquid quenching. This alloy does not typically require liquid quenching, so it is assumed that they were attempting to overcome the effects of excess nitrogen. There are mixed findings as to whether the properties can be recovered. Some researchers (Murr 2012) show that using an argon purge during the DMLS process can cause the material to respond correctly to heat treatment. The suppliers experience shows that this is not likely (Brancher 2015). Starr, et.al (2013) report that parts can regain properties through heat treatment, but once again, this does not appear to be the case in all instances.

With the stainless steel materials not being straight forward, the more exotic nickel and titanium alloys were evaluated. Inconel 625 would be able to be applied to the widest range of applications of any of the materials, including the stainless steels. The issue is that the minimum yield strength is approximately half that of 17-4PH. Inconel 718 has essentially the opposite problem in that it is too high of strength, and despite being acceptable for NACE applications, it has a yield strengths that violates the 120 ksi maximum yield strength required by paragraph 4.5.1.11 of API 617 (2014) for hydrogen service. Note that API 617 does not distinguish between material types in this requirement. Many of the impellers in this size range are used in applications such as hydrogen recycle compressors, so this is a significant concern. Titanium is not acceptable for hydrogen service and the plain Ti-6Al-4V is not acceptable for NACE service (ruthenium or platinum additions are required). It also has the issue of increased material cost and special handling since the material is highly reactive. Titanium powders are notorious for causing fires due to the intense heat generated by reaction with oxygen.

While all of the other projects used 17-4PH, with the possible questions as to where material in this condition fit in terms of issues like NACE acceptance, it was decided to us Inconel 718. This alloy is a work horse alloy for the gas turbine industry and due to that is one of the most well characterized and frequently printed materials. It was felt this would provide the overall best chance to properly investigate the abilities of DMLS to build an impeller to the desired tolerances. The API 6ACRA (2015) heat treatment was used for NACE compliance. Bhavsar, etal (2001) report that this heat treatment also appears to significantly improve the resistance to hydrogen embrittlement. This would have to be evaluated in more detail, but shows potential. It is also possible, if the DMLS process is shown to yield acceptable results, that processing parameters can be developed for other materials that may require fewer compromises.

After successfully printing a segment of the impeller in a feasibility study (Figure 23), it was decided to make the full impeller. Stock was added to the model this time, although being a near net shape process, more was added than probably necessary. Corrections were made for any distortion and sagging. The post printing processing, including HIP (hot isostatic pressing) and heat treatment to API 6CRA was kept the same. Figure 24 shows the impeller while it was still on the build platform. The supplier reported issues dealing with the part in this condition, since the build platform was thickened to help with distortion and the impeller itself, with the additional stock, was the largest/heaviest part they had ever made. It was processed as far as possible with the platform attached. Figure 25 are various views of the impeller after support removal and being cut from the base plate. As can be seen in these figures, the surface finish quality is very good considering the steps that form as a result of a layer-wise building process and the blade and flow paths appear to be very well formed. The impeller was abrasive flow machined in this condition to attempt to improve the surface finish of the flow path, particularly in the area where the supports were in place. The abrasive flow machining did create a near mirror finish on the flow path, but the surface is wavy, as it did not fully remove the small steps that denote the layers and some of the remnants of the supports remain (Figure 26). It was machined to the drawing dimensions after the flow path was treated. Figure 27 show the machined impeller in the same views as Figure 25 for comparison. With the exception of the flow path appearance, the impeller looks virtually identical to the EDM'd impeller previous discussed.

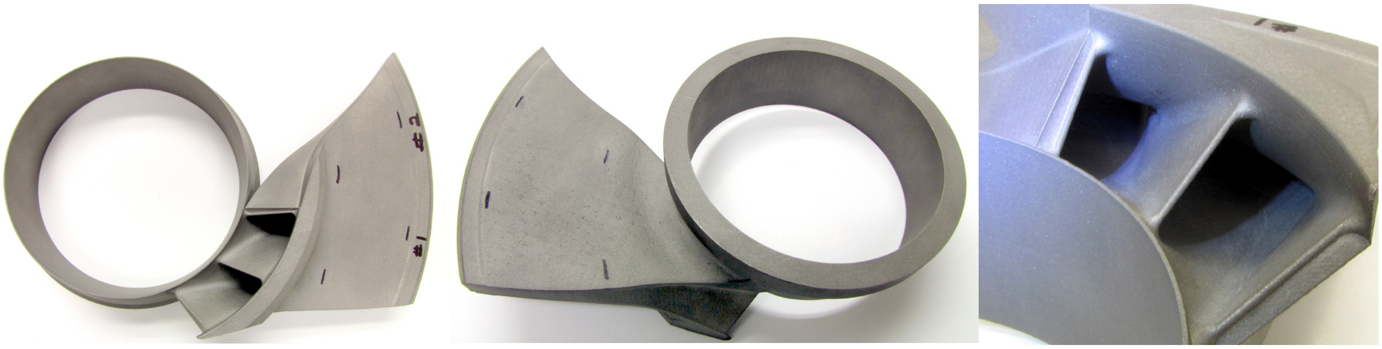

Figure 23. DMLS impeller segment

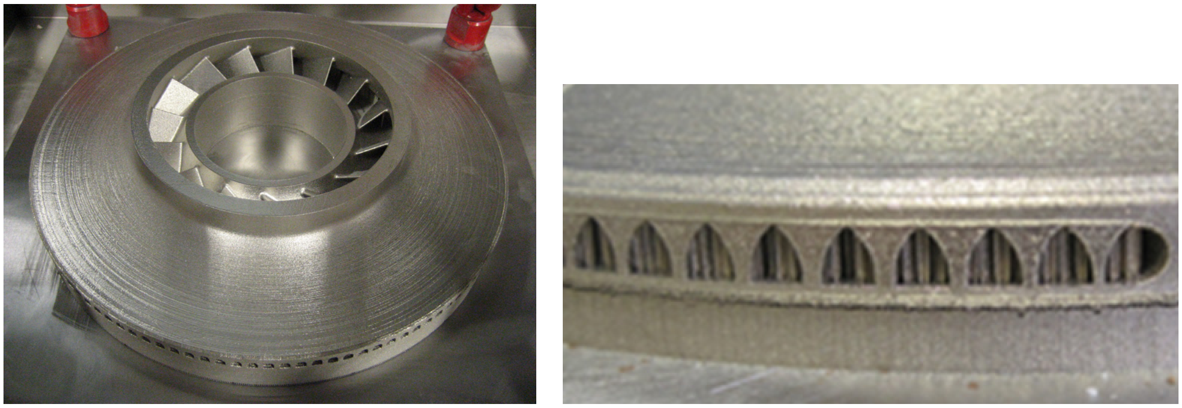

Figure 24. Image of the Full DMLS impeller as built on the baseplate

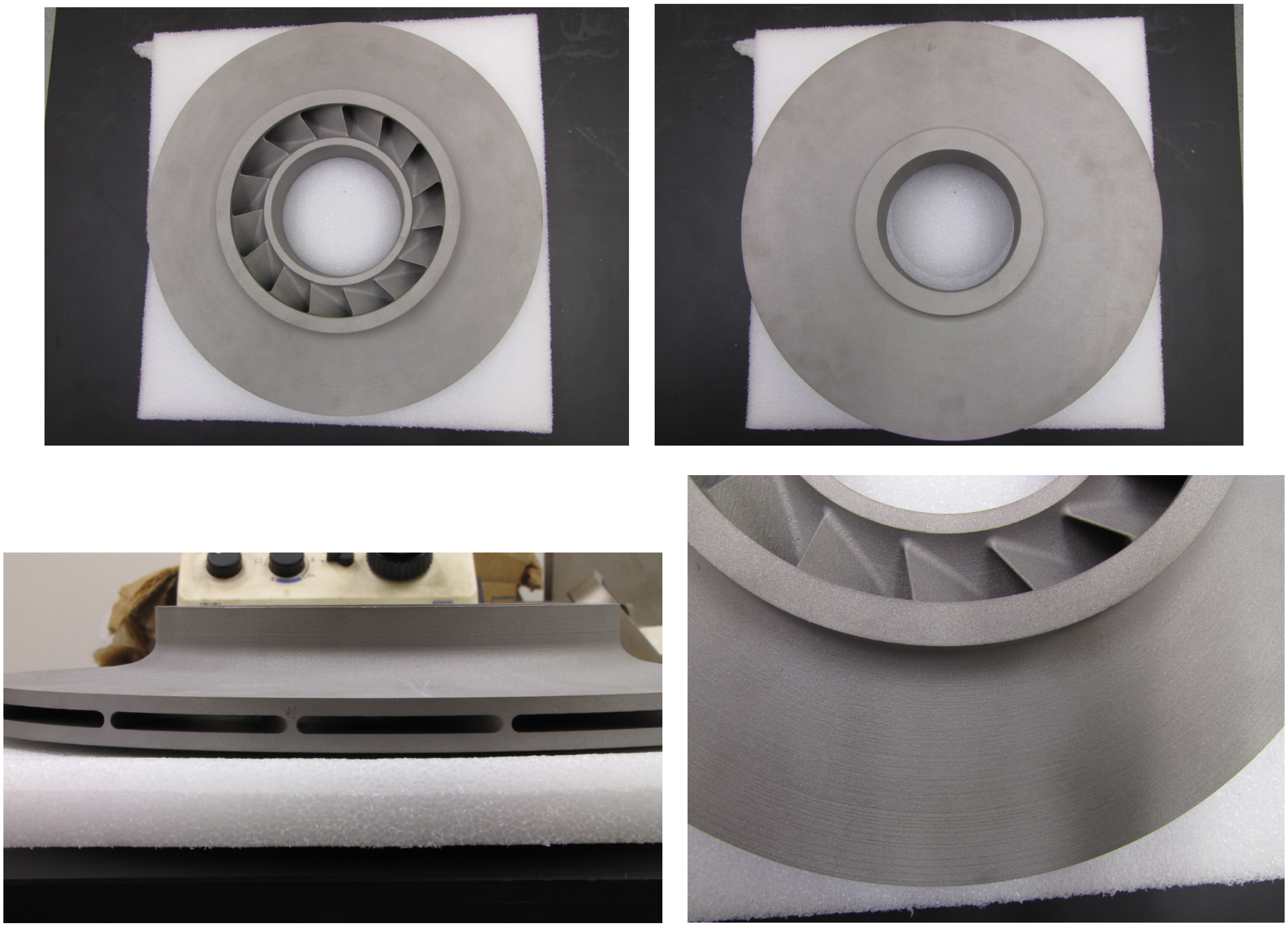

Figure 25. Various views of the DMLS impeller after removal from the baseplate

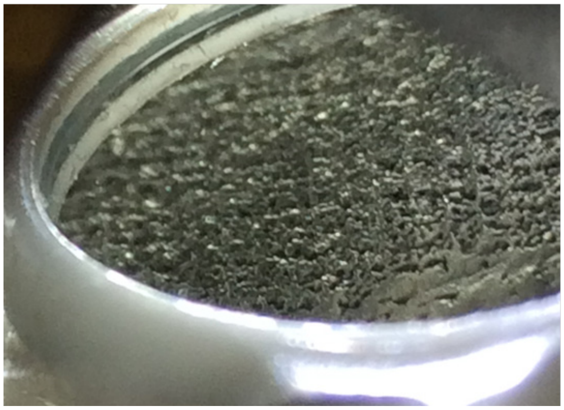

Figure 26. Reflected image in a 1” inspection mirror showing the remnants of the supports in the flowpath

The traditional dimensional checks performed on impellers during typical processing were performed on the impeller. There were only two dimensions that were out of tolerance and both were out by 0.001” or less. To conform to the other projects, the impeller would have been then cut apart and measured using the structured light process, but since this was meant to be a feasibility study that greatly exceeded expectations, there was a desire to keep the impeller intact. In order to get a better idea of the flow path dimensions without destroying the impeller, it was measured using X-ray Computed Tomography (CT). This is very similar to the CT scans used in the medical field and basically uses a series of X-rays to build up a 3D model of the actual part. This can then be compared to the design model for deviations. Figure 28 is two slices of the model in the axial direction showing the blade shapes. The vast majority of the blade/flow path surfaces are within the green/yellow color bands and are in tolerance. This indicates that the blades are very accurately printed. This statement is mostly true in the radial slices shown in Figure 29. These radial slices are a little more difficult to interpret. It is clear in Figure 29a that there is a raised area on the cover side of the flow path, which is denoted by the heavy concentration of red in the image. The blue areas further down the flow path in this Figure and in Figure 29c are not surprising since this is approximately where the support remnants can be seen/felt. What is confusing is that the outside of the hub in Figure 46 is a machined

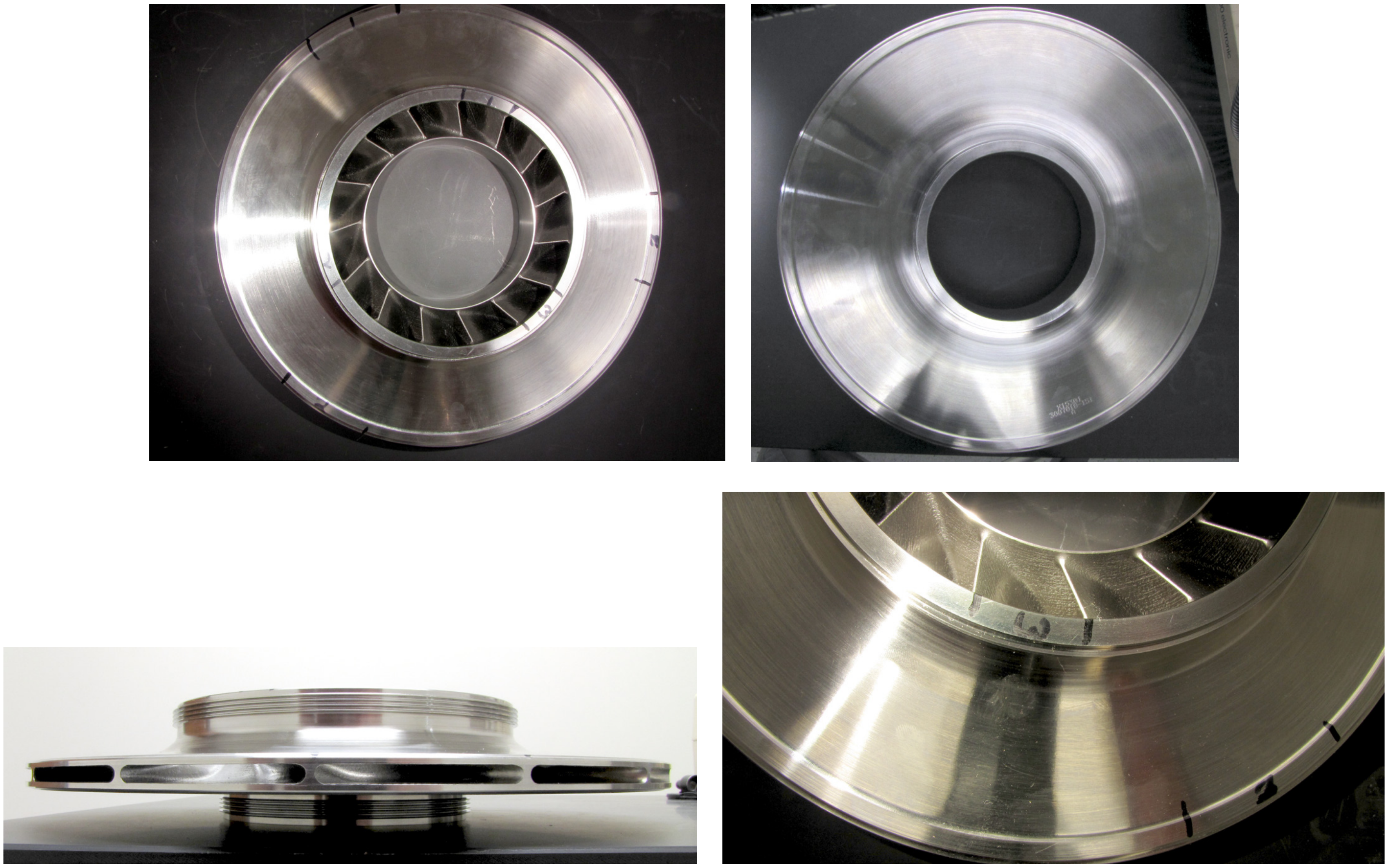

Figure 27. Various views of the finished DMLS impeller

surface appears as bad as or worse than some of the printed surfaces in the flow path. This is the case in other slices, but not in all. Part of the issue is that it is believed that the actual scans were done by axial slices and the radial slices are computed from them. This may have resulted in some errors. Given that the average printed surface is not significantly worse than the average machined surface in terms of deviations, it is believed that the impeller is very close, if not within tolerances. One further finding that can be determined using the X-ray CT method is that the impeller appears to be fully dense with no porosity observed.

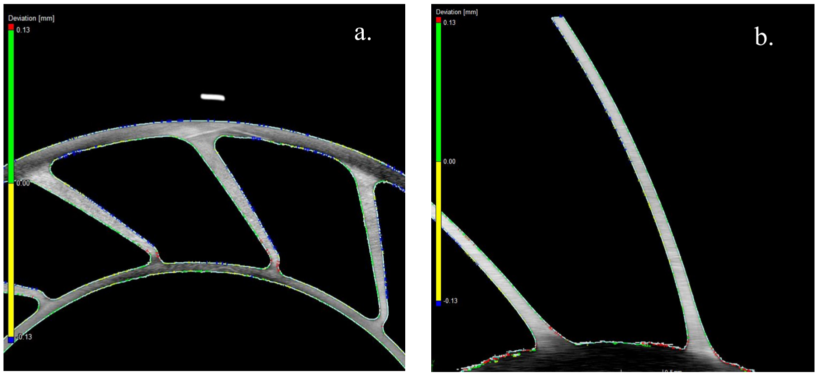

Figure 28. Comparison of X-ray CT results of an axial slice near the eye of the impeller (a.) and blade (b.) with the model

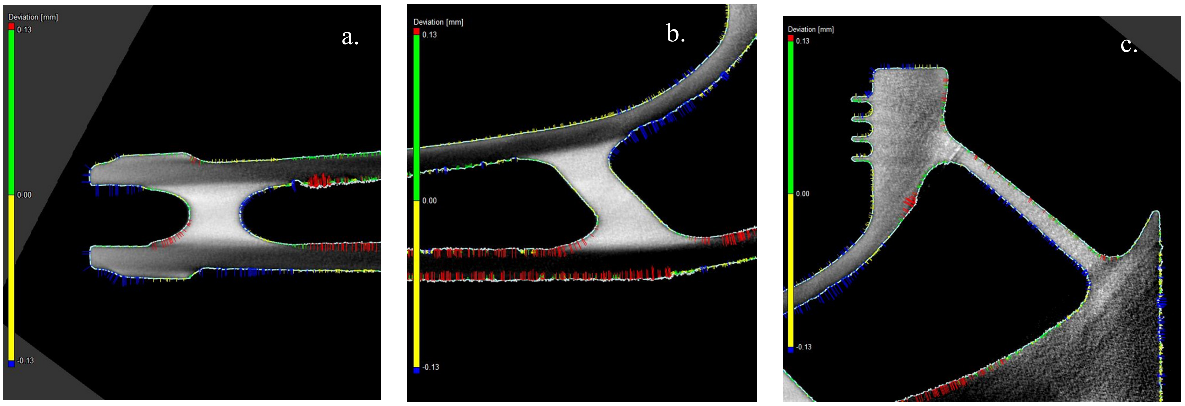

Figure 29. Comparison of X-ray CT results of a radial slice near the tip (a.), mid span (b.), and eye (c.) of the impeller with the model

Thus far it has been determined the printed part looks like an impeller and is shaped like it is supposed to be. The impeller was then rap tested in the same manner the EDM impeller was to determine if it behaves like an impeller. Comparing to the FEA predictions, the 2nd nodal diameter was 11% lower than predicted (Pechulis 2016). The frequencies for nodal diameters 3-7 are an average of 2.8% lower than the prediction. In comparison, the EDM impeller was only 5% lower than the predicted frequency for the 2nd modal diameter or about half the deviation observed in the DMLS impeller. Although they are in different directions, at ~2.2%, the EDM impeller is only about 0.6% closer to the predictions for the 3rd through 7th nodal diameters. With respect to the leading edge frequencies, the mean leading edge frequency of the DMLS impeller is 1-6.5% lower than the predicted range of frequencies with a standard deviation of 0.04% between blades. The EDM impeller was reported to be 9-15% higher than predictions with a standard deviation of 0.17%. This indicates that the blades of the DMLS impeller are possibly closer to the design shape and are more consistent blade to blade. The amount of mistuning is only very bottom of the range of recently tested 2 piece impellers.

The final checks on the DMLS impeller were to assess the properties and to evaluate the microstructure and integrity of the material. Table 2 shows the results of tensile tests performed on samples that were printed and processed with the impeller. Samples were printed in both the horizontal and vertical directions to determine if there are any significant differences between the two directions. The values were compared to the requirements of API 6ACRA for UNS N07718 – 120K. As can be observed in the table, the properties meet all of the mechanical properties. Furthermore, the hardness was 33.5-35 HRC, which is acceptable per NACE MR0175-2009 and to API 6ACRA. API 6ACRA required impact testing at -75°F (-59.4°C). The sample size was not large enough for a full size Charpy test bar, so the ft-lb requirement was not able to be determined, but the lateral expansion should not change drastically with bar size. Per the specification, the lateral expansion should be 0.015”(.38mm). For the purposes of the author’s company, tests were performed at room temperature and -150°F(-101°C). For both temperatures and both build directions, the lowest lateral expansion measured was 0.021”(.508mm). The samples were then cross sectioned to determine the presence of any porosity and to evaluate the microstructure. This is part of the API 6ACRA requirements as well. The structure is expected to be free of Laves phases, acicular phases, and continuous phases at grain boundaries. Beyond those requirements, being HIP’d material for a high stress application, the amount of porosity is expected to be very low or nonexistent. Figure 30a shows an image of the horizontal sample and Figure 30b shows the vertical sample. As can be observed, there are no deleterious phases and no continuous phases. There are no indications of porosity.

With respect to the material, all these tests were found to be well within the expected limits.

Table 2. Comparison of mechanical properties in both build directions

	YS (ksi/MPa)	TS (ksi/Mpa)	% Elongation	% Reduction of Area
API 6ACRA N07718 120K	120/827 min	145/1000 min	20	35
Vertical	123.8/854	169.9/1171	26.1	44
Horizontal	121.8/840	178.5/1231	27.5	35

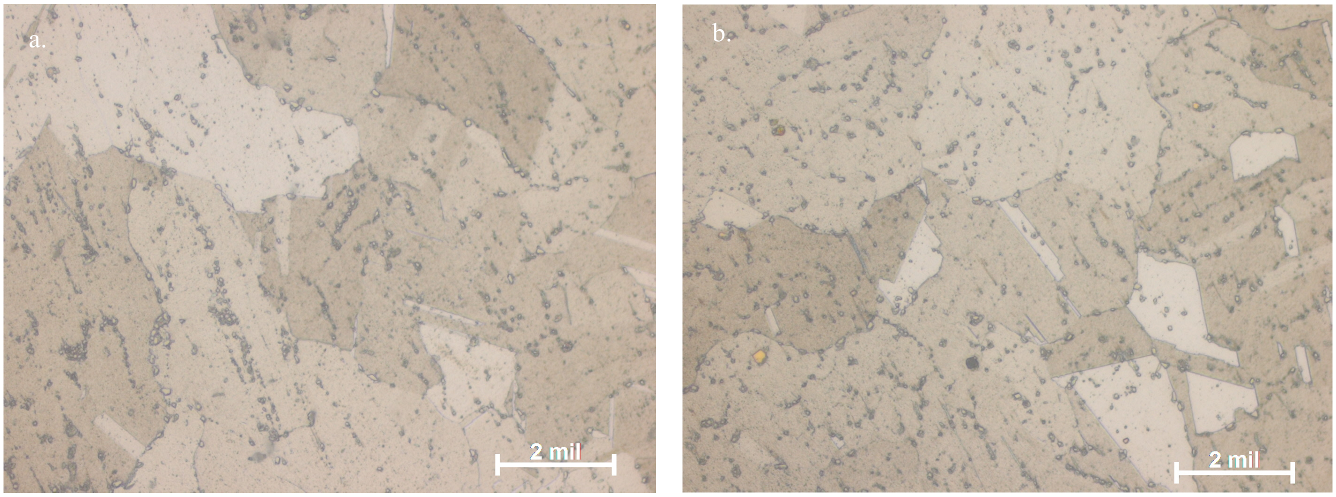

Figure 30. Cross section of the horizontally(a.) and vertically (b.) built DMLS samples (waterless Kalling's etchant)

DISCUSSION

When each supplier provided a quote for the developmental work for this project, they were also asked to provide an estimate of the cost if the impeller were for production. The in house processing was assumed to be the same for each method, regardless of incoming condition. The blue bars in Figure 31 are the comparison of the cost for each method relative to a 17-4PH brazed impeller. In this comparison, the investment cast impeller using the 3-D printed pattern and invested flow path (SLA IC) was the least costly and was actually less expensive than the brazed impeller. Using a ceramic core in the mold (Core IC) increases the cost such that it is about 50% higher cost than the brazed impeller. The EDM and DMLS are approximately 30% and 45% more costly, respectively. These could be considered over estimates, because these impellers would be coming in with much less finish machining required. The DMLS impeller is also a more expensive material. The equipment for these two processes are also within reason to purchase and develop in house, which also should reduce the costs. It must be noted that more recent quotations of a similar sized impeller using a DMLS type process were much reasonable and actually competitive with the investment casting costs.

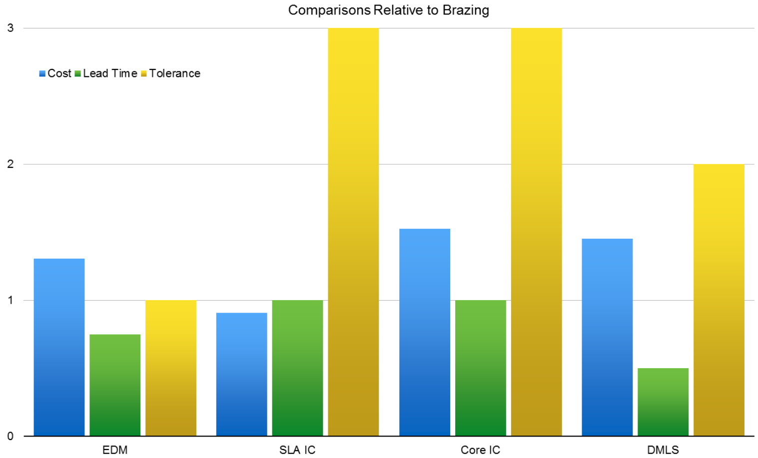

Figure 31. Comparisons to a brazed impeller

There are some surprising results for a similar analysis of the lead times for each method. Once again, these were based off of quotes from the suppliers. All of the methods were as fast as or faster than the standard time for the brazed impeller (green bars in Figure 45). The DMLS impeller has a major advantage in this area and was half the time of the standard. The segment that was made was reported to take just under two days to print and a full impeller took six days. This could be faster with less stock on the part. Most of the time and cost of this method are accounted for in the build height and not the extent or complexity required in the horizontal plane. EDM was the second shortest time and was 75% of the time of the brazed impeller. Once again, both of these could be faster if the equipment was in house, as most of the lead time is tied up in scheduling rather than actual work. While investment casting does also have the scheduling issue, there is a significant time in processing these impellers. The pattern print time is similar to the build time of the DMLS impeller, the investing process can take a week, heat treating can take a week, and upgrade cycles could take significant time. The ceramic core also adds significant time, so the invested flow path option is expected to be faster, but the supplier quoted the same lead times for both.

It was mentioned above that the tolerances the suppliers were given were 5 –axis milling tolerances. It's not shocking that EDM showed the best performance in meeting those requirements. It is a mature, entirely subtractive process that is indexed and computer controlled. It easily met all of the dimensions that are typically checked in a production impeller. Surprisingly, the DMLS impeller appears to be a relatively close second. The investment cast impellers using printed patterns and cores do not prove to be up to the task of meeting the tight requirements of an impeller when used for one off parts. While the suppliers may be able to tighten the ranges up on future impellers, it is highly unlikely they will be able to match the tolerance requested without a number of iterations. This was the same for powder metal parts. Aerodynamics engineers at the authors company are working on a sensitivity study to determine how wide the tolerances can be before any significant changes to the performance are expected. Early indications are that the acceptable tolerances for design will be within the range of what is achievable with these processes.

There is also the issue of surface roughness. The EDM impeller had a very good surface finish that required no further work. One of the chief advantages of investment casting over sand casting is its ability to replicate the smooth and intricate surfaces of the pattern, so it is also capable of acceptable surface finishes. That being said, if a ceramic core is used, there is a risk of burn in, which results in a very rough and inconsistent surface finish in the flow path where corrections may not be possible. Powder metal should replicate the finish of the insert, so the only risk to the surface finish is if the acid used to remove the insert begins to attack the base material. Careful selection of acid should limit that. That leaves DMLS. The results here show that this is an issue for narrow flow passages that require supports. It is difficult to remove all of the remnants of the supports. Even in the absence of supports, down skins (surface facing the build plate in a print) typically have a significantly rougher finish than up skins in the best of conditions and can be as bad as or worse than the support remnants in conditions that cause fused agglomerates of melted powder to form and adhere to the down skin. Recent work with a support free build does show, with care, the down skin can be greatly improved and approach the up-skin finish. Work has been done to attempt to correct the surface finish on the segment piece that was printed, but no acceptable process has been found to date that will work the offending areas and leave the rest unaffected. Further complicating this issue is that regardless of the down skin condition, the surface is variable due to the layer-wise build and change in angle in the part. This makes assessing the impact of the surface finish difficult to physically and computationally evaluate in terms of impact of performance, be it aerodynamic or mechanical.

CONCLUSIONS

Overall, all of the processes being evaluated in this work are capable of producing impellers in this size range. It is truly a matter of perspective if one was to rank them in terms of suitability. If the situation was different and the same design of impeller was mass produced, HIP'd powder metal and investment casting suppliers could perfect the required tooling and would be difficult for additive manufacturing or EDM to match for cost and possibly lead time. Conversely, each of these is in a different state of readiness with respect to implementation in a custom, one off type application. From this perspective, EDM is clearly the most advanced and ready for application and in fact, there are already impellers in service made using EDM. The work on the other processes hasn't progressed far enough for hard conclusions, but investment casting and additive manufacturing appear to be very viable. Additive, in particular, is exciting, because it is fairly new and the surface has barely been scratched with respect to what it might be capable of.

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