Reverse Engineering of Pump Impeller Utilizing Rapid Prototyping Technology

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ABSTRACT

Utilizing the manufacturing procedure of product mostly depended on physical characteristics, accessible facilities and desired specifications of product. In addition, procedure lead-time and economic issues are the effective parameters, which are investigable in planning procedure of every product. Pump manufacturing industries as one of the Precursor industries has also involved with some challenges in both design and manufacturing phases of production. The pump impellers as the main part of pumps are considered in this regard. The shape of impellers characterizes the performance and application of pump. Complicated blade shapes manufacturing is also needed to skilled workforce as well as implementing high technologies and equipment's.

3D blade shapes impeller reverse engineering as the objective of this thesis is investigated in follow steps:

a) Utilizing Rapid Prototyping method in reverse engineering as objective of this thesis has been studied and compared with conventional and CAD/CAM method with considering to time and cost issues.

b) Pump hydraulic test analysis demonstrate the degree of compliance among reverse manufactured pump and the original pump. Parameters including Head (H) and Flow rate (Q) have been studied in case of conventional manufactured impeller and RP utilized impeller. The results have been investigated in two diagrams separately.

Keywords: Reverse Engineering, Rapid Prototyping

ÖZ

Urünün üretim prosedürü kullanimi, Çoğunlukla fiziksel özellikleri, erişilebilir tesisleri ve ürünün istenilen özelliklerine bağlıdir. Ayrıca işlem kurşun süresi ve ekonomik konular her ürünün planlama prosedürü araştırmali olan etkili parametrelerdendir. Pompa imalat sanayileri ayrıca üretim tasarım ve üretim aşamalarında hem de bazı zorluklar ile ilgili olan Öncü sektörlerden biridir. Pompaların ana parçası olarak pompa pervaneları bu konuda kabul edilir. Pervane şekli pompanin performansı ve uygulamasına işaretedir. Karmaşık pervane şekilleri imalatı da kalifiye işgücü yanı sıra, yüksek teknoloji ve ekipman uygulayıcı için gereklidir. Bazı durumlarda üretici stratejileri karmaşık çarkları üretmek için uygulanan ters mühendislike bağlıdır. Bu tezin amacı olarak 3D pervane şekiller çark tersine mühendislik takip adımlarla incelenmiştir:

a) Bu tezin amacı olarak tersine mühendislik kullanarak Rapid Prototyping yöntemi okudu ve zaman ve maliyet sorunları dikkate alarak geleneksel ve CAD / CAM yöntemi ile karşılaştırılmıştır.
b) hidrolik test analizi uyum derecesi ters imal pompa ve orijinal pompa arasında gösterirler. Head (H) dahil Parametreler ve Akış hızı (Q) geleneksel imal pervane ve RP kullanılan çark durumunda çalışılmıştır. Sonuçlar ayrı ayrı iki diyagramlarda incelenmiştir.

Anahtar Kelimeler: Tersine Mühendislik, Rapid Prototyping

To my Family

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Chapter 1

INTRODUCTION

1.1 Introduction and Research Motivation

Increasing advancement of science and technology led organization to use more and more pumps with some new characteristics in their industry. Indeed pump is a machine which are used for transferring the fluid from one to another level of head [1]. Mechanisms of most pumps are similar to each other's, they transform kinetic energy to the dynamic energy of the fluid and aiming to flow transferring. Pump manufactures has been passed a significant progress in the last decades. Due to the urgent needs of industry, still there exist a huge amount of investment in this sector which are ultimately leads to improvement in design and manufacturing of this specific product.

Commonly, pump manufacturers have been involved with many challenges, not only on design phase but also in manufacturing, test, and prototyping. Similar many other produces in different sectors, pump manufactures are seeking for the technologies and approaches to reduce manufacturing costs and time as well as improves the quality [1]. In this regard, the reverse engineering and re-engineering paradigms has been highlighted by many of the manufacturers in this sector. Also many of these efforts are caused to improve some parts of the desired factors, however it still an urgent need is feeling to need for technologies and approaches for much more improvements in this context.

Nowadays, some new technologies are going to employed in designing phase of the pump aiming to reach required parameters as well as better performance (i.e. fluid behavior and analyses using FEM and CFD methods) [2]. Since, the design and testing procedures of a pump (in compare to manufacturing phase) are so costly and time consuming therefore in most of the cases small and medium size pump manufacturers prefer to use the exist products form the big manufactures and depend of their needs just do a re-engineering and or reverse engineering. During reverse engineering and/or re-engineering process they use special technology inevitably to enable to implement any changes to improving and customizing it [3]. Reverse engineering is not only decreases design costs but also it enables the manufacturer to have any changes in base design so easily which are resulted in improvement and customizing the procedure. So selecting the most efficient and applicable way in reverse engineering is the argued issues in this regard [4]. Also RFID based system such as [5] for RP and FMS system [6].

Proportionally it has been conventional method in reverse engineering processes which are involved but not limited to: casting, machining, conventional hand craft technics. With emerging Rapid Prototyping (RP) and Rapid Tooling (RT) technologies in this sector, this approach has been faced with great revolution. Mechanisms of most rapid prototyping technics are somehow similar and impart additive layer systems and the differences are in material and layer joining mechanism [7].

The ability of producing complicated shapes parts with high accuracy in short time are the main advantage of RP and RT technologies Moreover, this technology realized physical and testable prototypes for the sector before time consuming and costly mass production [8]. These kinds of prototypes are improves the designers and manufacturers capabilities on easy modifications and improvements [9].

Using RP technology in reverse engineering might be an effective. In this thesis a novel RP-based approach is proposed as a tool for effective reverse engineering for pump manufacturing. In this regard, RP technology is used reverse engineering pump employing sand casting process. A special industrial pump of petroleum industry will be investigated exclusively and the efficient parameter will be discussed in detail.

1.2 Research Aims and Objectives

The rapid prototyping (RP) technology is a stimulating new technology, which is used for quickly creating physical models and functional prototypes directly from CAD models. The ability to manufacture complex blade profiles that are robust enough for testing, in a rapid and cost effective manner is proving essential so the main aim of this thesis is employing RT on sand casting process of an industrial pump.

Reverse Engineering of pump impeller utilizing RP technology has been studied to specify the degree of compliance between the original pump and reverse manufactured pump. Case study is 3D blade shape impeller and it classify as one of the intricate blade shape to manufacturing. Utilizing RP method in case of reverse engineering not only overcome the intricate blade limitations in case of manufacturing also will reduce lead time and manufacturing costs. Initial objective of this thesis would be investigating the capability of RP technology in case of reverse impeller manufacturing and the second aim would be approach to Time and cost optimization.

Totally the motivate reason to implement RP technology in reverse engineering of pump impeller categorized as follow:

- RP is an appropriate technology for producing complex shapes (e.g. pump impeller)

- Intransitive time to producing first pattern is so low compare to other methods

- Relatively the cost is also so low both in work force issue and technical requirement.

- There is no need for expert work force to produce pattern

- Flexibility during the procedure due to CAD data which is patched to RP machine, so any changes in date can transform to the machine easily.

- The model which is producing via this technique dimensionally is accurate, has adequate surface quality and structurally is robust enough to implement tests before mass production.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Nowadays pumps are one of the most electrical power consumers of industry. they are used to transferring flue from specific level to high level [10]. Mechanisms of most pumps are look like together. Commonly they transform kinetic energy of fluid to dynamic energy. These procedure is done by the specific mechanism of every pump [1].

Pumps common classification can presents as follow: positive displacement, kinetic, and direct lift pump. Centrifugal pump as the subset of kinetic pumps are the most applicable and popular in this regard. Main part of centrifugal pumps is impeller. Commonly impeller rotational movement causes to fluid suction inside of the housing and enhancing the pressure is done by transferring the kinetic energy. The enhanced pressure passed through the outlet of casing and performed the pumping operation [11]. It was briefly explanation pump applicant mechanism, more detail about performances and construction will present in next parts.

Pumps have also many variable application, for instance in biology cases, many different kind of bio-mechanical and chemical pumps have evolved, and bio mimicry is also used in improving new kinds of mechanical pumps [12] (Lobanoff & Ross, 2013).

2.2 Pumps Classification

There are so many different kinds of pump classification but commonly Classification of pump bases on the fundamental of the applications which they will serve their own functions, properties of constructed material, the type of the liquids that they handle, and even their direction of installed formation. All kind of these classifications are limited by the subjects of their unique characteristics, so it will not overlap each other's substantially [13].

The essential classification of basic system is defined by whichever energy added into the fluid of pumps. It causes the principle of identification can be shown and implemented such as delineates specific geometries. Figure1 demonstrate the exist pump classifications.

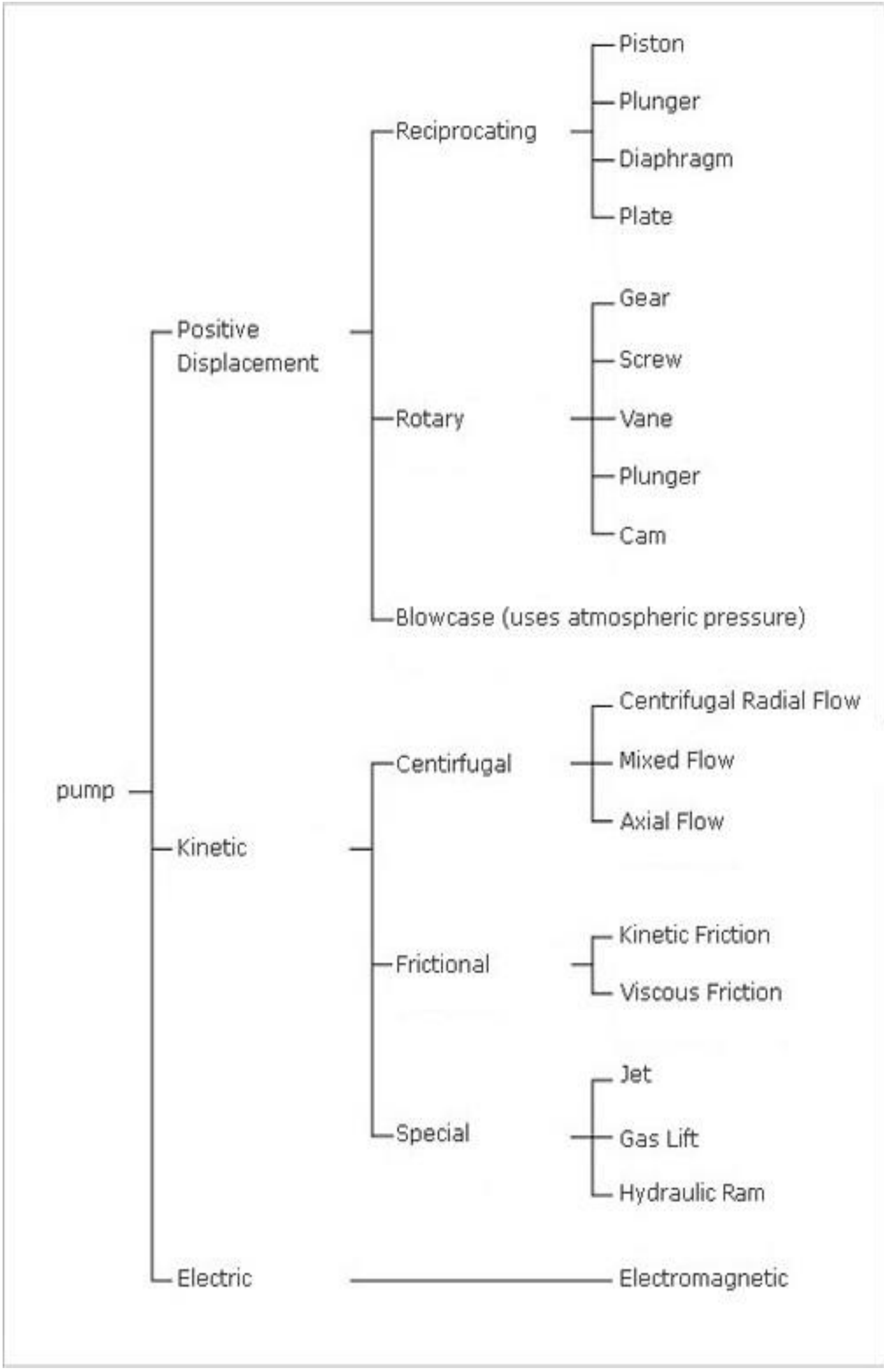


Figure 1: pump classification based on fundamental of the applications [13]

since in this dissertation we are going to focus on manufacturing issues of centrifugal pumps, briefly the next section tries to highlights some general terms related to these pump types.

2.2.1 Centrifugal pumps

Centrifugal pumps are a sub-class of dynamic ax symmetric work-absorbing turbo machinery. Centrifugal pumps are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. The fluid enters the pump impeller along or near to the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber (casing), from where it exits [1]. Figure 2 demonstrates the working mechanism of the centrifugal pumps.

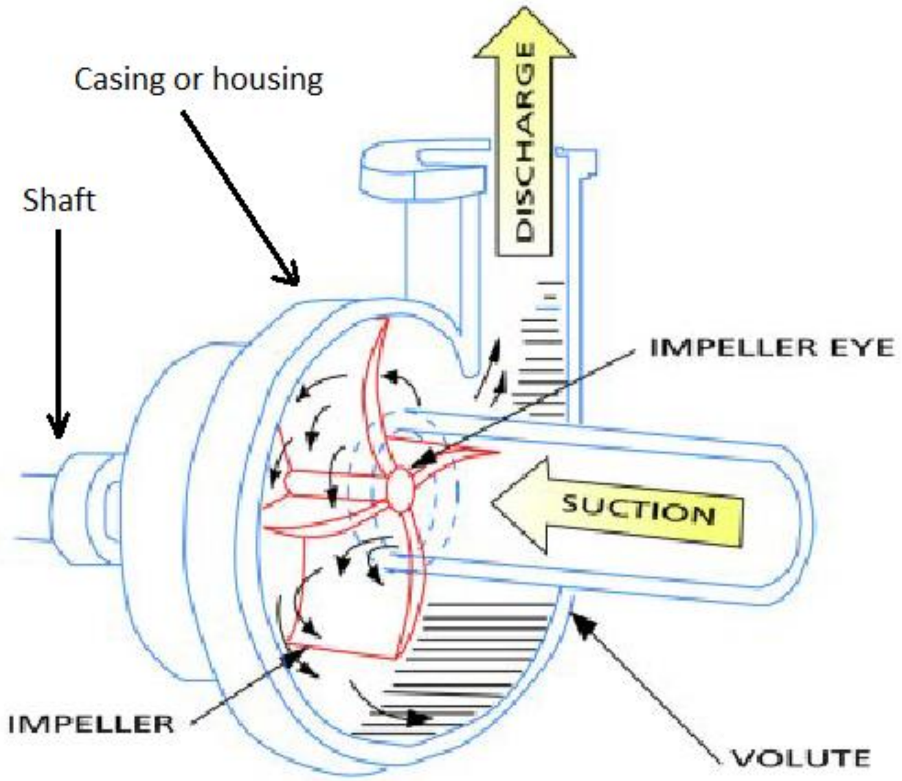


Figure 2: The mechanism of centrifugal pumps [13]

As it shown in the figure 3 this type of pumps has an inlet for sucking flue. The impeller is located inside of housing. Housing also is a sealed and closed case. Impeller gets the kinetic energy through the shaft which is coupled to electromotor or other power sources. Kinetic energy of impeller is transferred to flue via blades (vanes). Now the flue is under the pressure and has energy so traverse the outlet way to discharge. That’s the general operation mechanism of all centrifugal pumps. Figure 3 shows the all segment of one centrifugal pump [14].

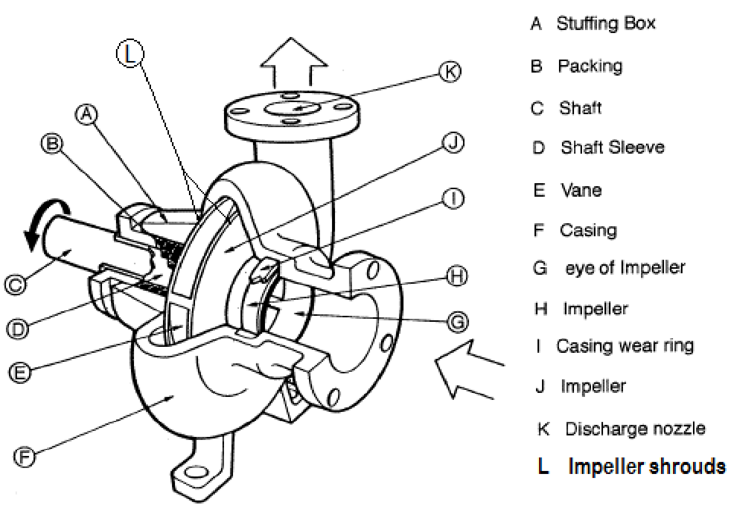


Figure 3: Centrifugal pump component [13]

Impeller

The rotating element of the pump which imparts the force to the liquid. The impeller has vanes (or blade) which vary in number and discharge angle to give the desired performance.

Impeller eye area

The net opening of the impeller, usually the area of the impeller suction less the area of the vane blockage.

Packing or Mechanical seal

To prevent leakage the under pressure liquid inside to outside it has to be sealing on the shaft which enters the housing. Packing or mechanical seals are installed at the back side of housing on the shaft and do sealing duty.

Impeller Shroud

Part of impeller casting which is a circular disk that encloses the impeller vanes; front shroud refers to one on the suction side, back shroud refers to one on the opposite side [14].

2.2.1.1 How it works

Mechanisms of most pumps are look like each other. Centrifugal pump transforms mechanical energy of motor to moving energy of fluid. Portions of the energy convert to kinetic energy of the fluid. Fluid enters in axially direction through eye of the casing section, is caught up in the impeller blades, and is also rotated radially and tangentially outward until it leaves through all circumferential section of the impeller into the diffuser section of the casing. Fluid gains both pressure and velocity while passing through the impeller. The doughnut-shaped diffuser, or scroll, section of the casing decelerates the flow and further increase the pressure [15]. Centrifugal pumps can be further differentiated based on how they direct flow (Bloch & Budris, 2004).Figure4, 5, 6 and 7 illustrated axial flow centrifugal pump.

- **Axial** flow pumps lift liquid in a direction parallel to the pump shaft. They operate essentially the same as a boat propeller.

- **Radial** flow pumps accelerate liquid through the center of the impeller and out along the impeller blades at right angles (radially) to the pump shaft.
- **Mixed** flow pumps incorporate characteristics from both axial and radial flow pumps. They push liquid out away from the pump shaft at an angle greater than 90°.

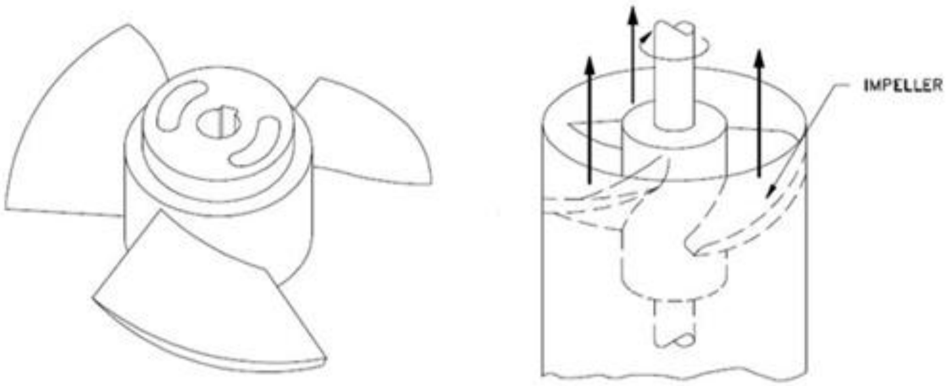


Figure 4: Axial flow centrifugal pump (Boyadjis, P. A, 2001)

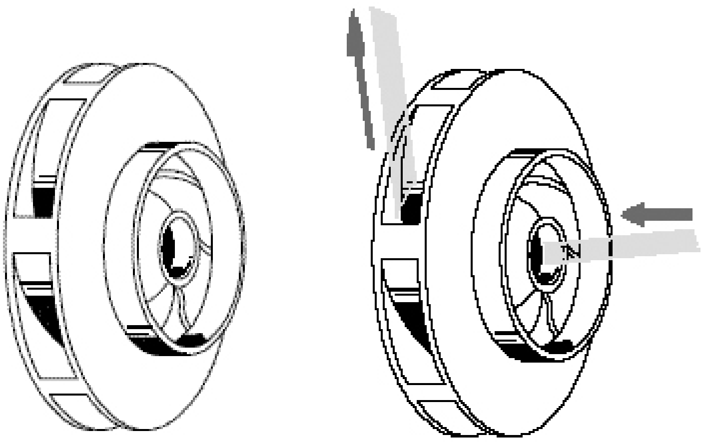


Figure 5: Axial flow centrifugal pump (Boyadjis, P. A, 2001)

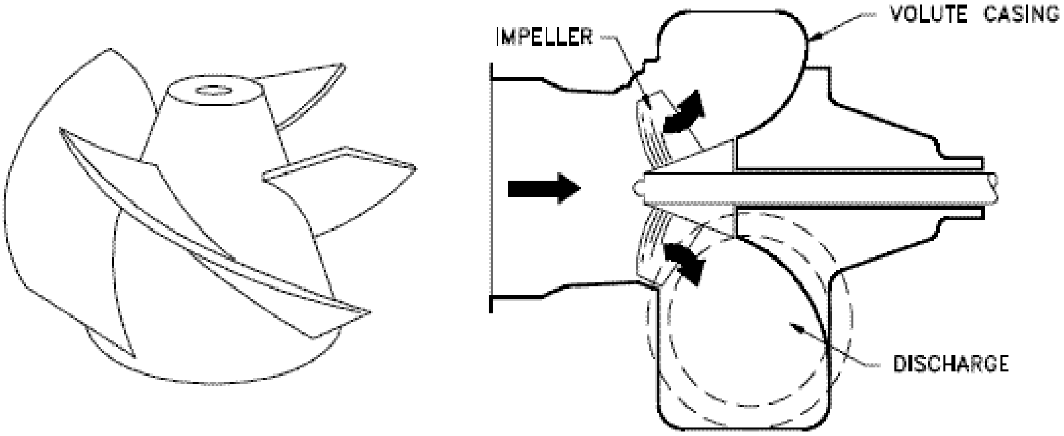


Figure 6: Mixed flow centrifugal pump (Boyadjis, P. A, 2001)

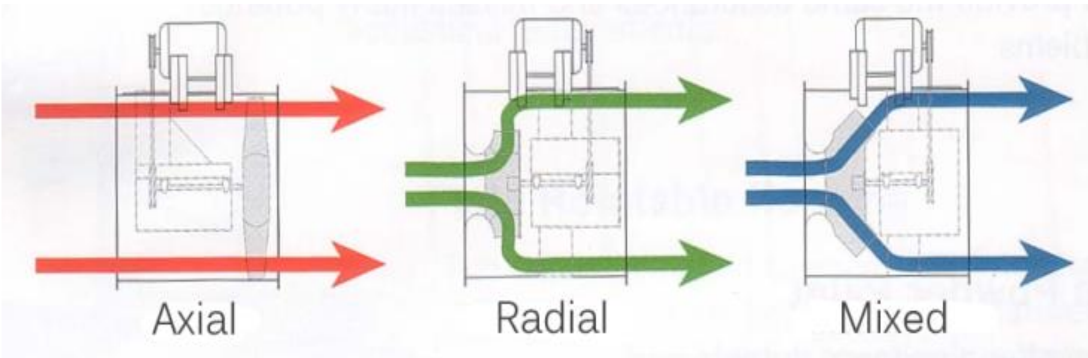


Figure 7: Comparison figure [13]

2.2.1.2 Functional Comparison between Axial Radial and mixed Flow Impellers

In Radial-flow, pumps operate at higher pressures and lower flow rates compare to axial and mixed-flow pumps. Axial flow pumps operate at higher flow rates and much lower pressures than radial-flow pumps. Mixed-flow pumps operate at higher pressures than axial-flow pumps while delivering higher discharges than radial-flow pumps. The exit angle of the flow dictates the pressure head-discharge characteristic in relation to radial and mixed-flow [16].

2.2.1.3 Advantage and Disadvantage of Centrifugal pump

Simple in construction and cheap Handle liquid with large amounts of solids, No metal to metal fits, No valves involved in pump operation, Maintenance costs are lower. PUMP cannot handle highly viscous fluids efficiently, cannot be operated at high heads, Maximum efficiency holds over a narrow range of conditions.

2.2.1.4 Impeller

An impeller is a rotating component of a centrifugal pump, and actually is the heart of every centrifuge pump. Depending on the expected application it can be manufactured in many different shapes and materials. [17-19]. Sometimes it has so complicated shape and production of that is a great challenge to manufacturer. There are many diverse way to manufacturing impellers. Traditional way such as casting or machining and in some cases especial advanced manufacturing technology have selected by pump specialist. So every time the manufacturers have to note the parameters such as the flue type and the expected velocity and pressure and involved them in manufacturing procedure. [1]. In future sections we want to investigate any type of centrifuge impeller and the ways to how produce them. Figure 8 shows the main part of impeller via eye of impeller.

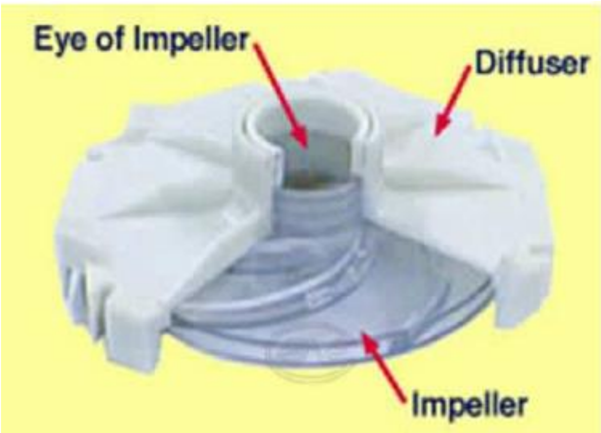


Figure 8: main part of impeller [1]

2.2.2 Classification of Pump Impeller with Consideration to Their Manufacturing Process

Pump impellers (centrifugal pump) are manufactured ordinary in two types[20]: the Open impeller shape and (or semi open), Closed impeller shape shown in Figures 9 and10

Figure 9: open impeller [1]

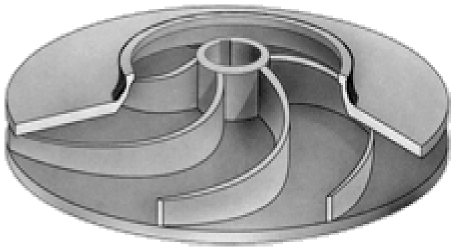


Figure 10: close impeller [13]

In addition to open or close type they can be classify by 2D or 3D shape of blades. There exist four different types of impellers as following: Figure 11, 12, 13 and14.

1. 2D blade open impeller
2. 3D blade open impeller
3. 2D blade close impeller
4. 3D blade close impeller

Figure 11: open 3D blade impeller [1]

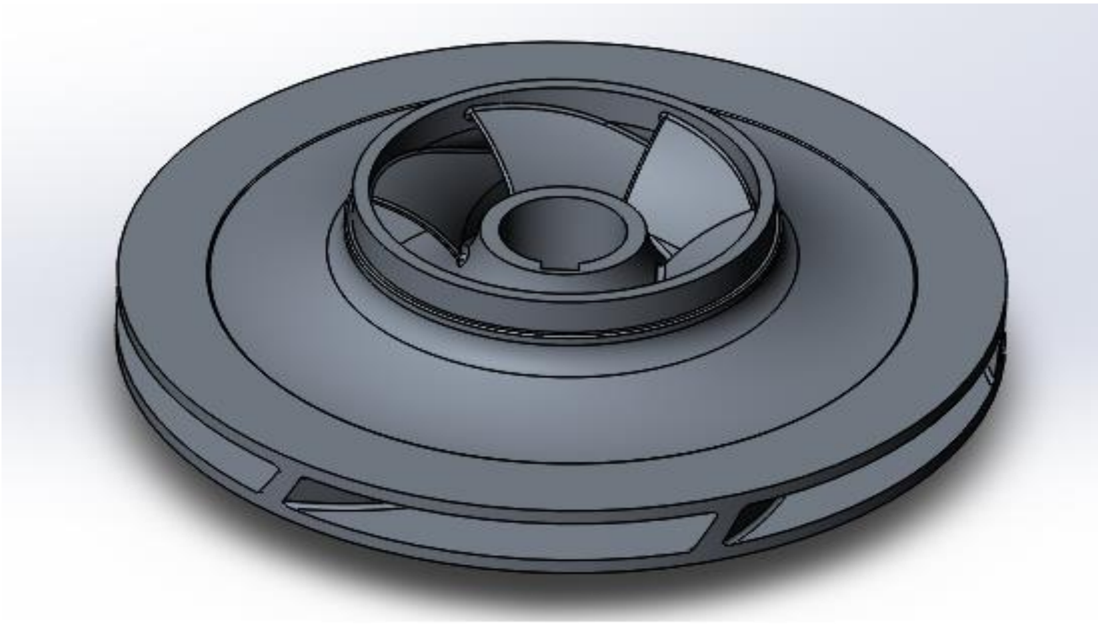


Figure 12: 3D blade close impeller

2.3 Process and Methods for Impeller Production

It mentioned before as a manufacturing point of view, pump impeller can be classify as close or open which can be in 2D or 3D types. Therefore, it would be better to investigate the manufacturing process with consideration to it shape and types.

The common and usual global of pump impeller manufacturing can be presents as follow [20].

- Sand casting method
- Machining
- Welding or some other joining procedure
- Rapid prototyping and rapid tooling

The sand casting method is the most popular and applicable methods among the impeller manufacture. Low cost and convenient in technological terms made this technology pervasive compare to other methods. In addition, it has some limitation which compel manufacturer to select other methods as well. Afterword this technology will be investigated completely in case of directly and reverse engineering of impeller manufacturing and advantage and disadvantage will be presented completely [21].

2.3.1 Sand Casting Process

A process used to form solid metal shapes out of molten metal. The molten metal is poured into a cavity or a mold. Figure 12 shows sand casting mold with elements.

Sand casting is used to make large parts (typically Iron and Steel but also Bronze, Brass, Aluminum). Molten metal is poured into a mold cavity formed out of sand (natural or synthetic). The processes of sand casting are discussed in this section; include patterns, sprues and runners, design considerations, and casting allowance.

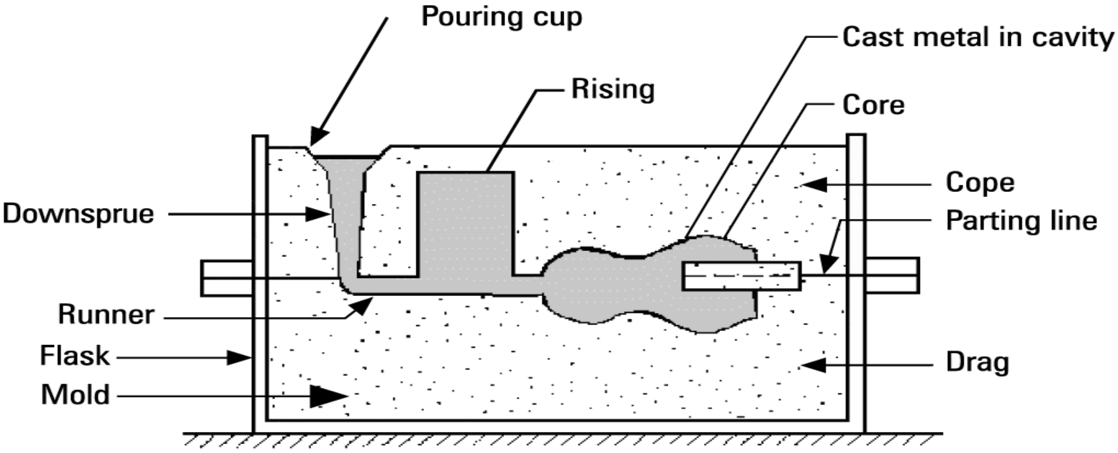


Figure 12: sand casting mold with elements [22]

Sand casting is one of the old techniques, which are now improved, and it can still compete with other production procedure. Approximately 75% of castings products are made in sand molding which they do not completely satisfy the required accuracy and surface finish. Because of this reason most improved methods such as investment castings, shell molding, die castings; etc. are finding wider application [22].

Operation sequences are consisting of:

- Pattern making.
- Mold and core making.
- Melting and Pouring.
- Fettling or Trimming.
- Inspection

In addition, there are other methods of casting, dependently to desired feature, are implementable. In next table compression to other methods and advantage, disadvantages and limitation of every method are summarized in case of impeller [22].

Table 1: Sand Casting Compared with other Casting Method [22]

PROCESS	ADVANTAGES	LIMITATION
Sand Casting	**1. Any metal is cast** **2. No Limit to size and shape** **3. Low tooling Cost**	**1. Poor surface Finish** **2. Requires Machining**
Ceramic Moulding	**1. Intricate shapes can be produced** **2. Good surface Finish** **3. Close dimensional tolerance**	**1. Size of casting Limited**
Shell Moulding	**1. Good dimensional accuracy** **2. High production rate**	**1. Part size is limited** **2. Expensive patterns and equipment required**
Die Casting	**1. Good surface finish and dimensional accuracy** **2. Low porosity** **3. High production rate**	**1. High mould cost** **2. Not suitable for intricate casting** **3. Not suitable for high melting point metals**
Centrifugal Casting	**1. Large cylindrical parts** **2. High production rate**	**1. Requires costly equipment** **2. Part shape limited**

Some advantages of Sand Casting **:**

- Casting process can be performed on any metal that can be heated to the liquid state.
- Some casting methods are highly suited for mass production.
- It is suitable method to producing complicated shapes

Some disadvantages of Sand Casting:

- Limitations on mechanical properties.
- Porosity (empty spaces within the metal – reduces the strength of metal).

- Poor dimensional accuracy and surface finish.

In pump impeller manufacturing there are some method which implemented via manufacturers, as mentioned before sand casting is one of the way, presented advantage and disadvantages. Look like other casting procedure it needs to prepare pattern firstly and then other step will come subsequently [23]. All the steps are shown completely in figure 13 we would focus mostly in pattern manufacturing section.

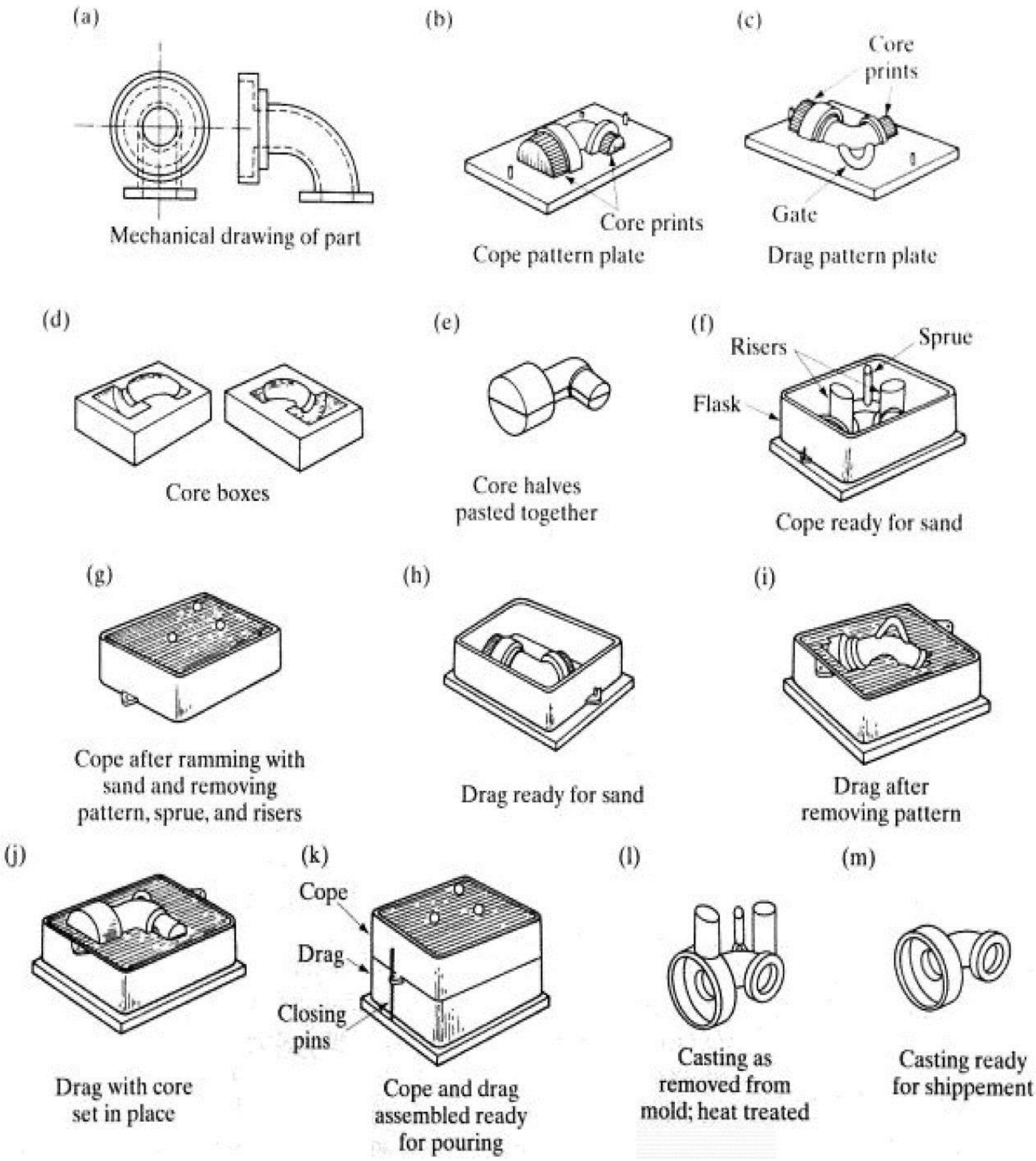


Figure 13: Overview about sand casting procedure

Why sand casting process is good for impeller production:

Nowadays sand casting is also most common method in impeller manufacturing because of inherent feature of this method which makes it possible to molding the complicated shapes, also as beneficial way with low cost and no need to very professional labor. All of these can be mention as advantage of sand casting to produce pump impeller. But as mentioned before about disadvantage of sand casting all those are also true in case of impeller sand casting especially as poor surface and not very accurate dimension point of view. These limitation are also controllable are reducible via precise molding procedure.

2.3.2 Machining process for impeller production

This method mostly used in case of complicated shape impeller. This procedure among the other method is so costly because it needed to CNC machines and expert labors. The routine is like that, design procedure is done via CAD software, then these data analyzed by CAM software such as POWER MILL and other software, tool path and other parameters defined by this software and transferred to CNC machine.

Most of the time 5 axis CNC machine is needed to manufacturing the curves. In normal 2D and not complicated impellers there is no need to use 5 axis CNC and it applicable via normal 3 axis CNC machine and the procedure is the same. It need to mention this fact this way is applicable directly just in manufacture of open impellers, but it is also applicable to produce assembled pattern in case of casting procedure. Actually whenever it needs to produce so accurate pattern, this method is so applicable.

In this case we use produced impeller as a pattern in casting procedure. So it is indirectly use of machining in impeller manufacturing. Moreover that is applicable in reverse engineering [24]. More detail about machining application in case of reverse engineering will be discussed in next chapters. Figure 14 and 15 presents Machining procedure overview and CNC impeller machining.

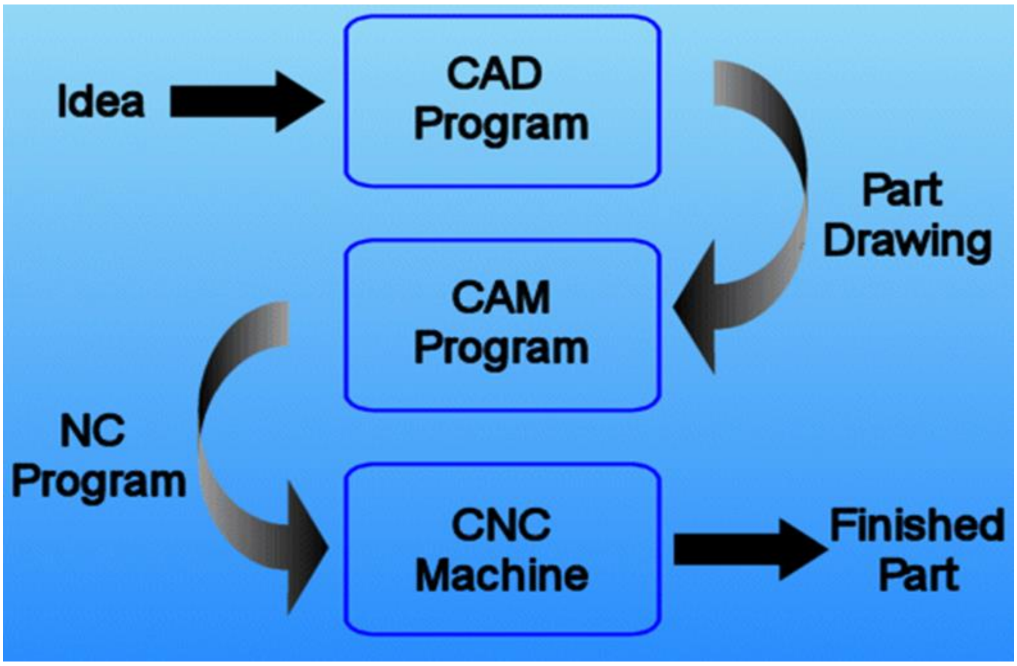


Figure 15: Machining procedure overview [24]


Figure 16: Directly machining of impeller via CNC machine

Indirect use of machining in impeller manufacturing

Indirect way utilized to pattern manufacturing in casting procedure. To achieve the application it need to produce so precious pattern and also core box. As it mentioned before pattern material dependently on expected desired feature can be iron, brass, plastic or even wood. There are many way to make pattern. One of the common way as it mentioned is machining. This way is indirect way to producing impeller and machining is just used to producing pattern. Dependently on pattern shape normal machining or CNC machining can be select. For so complicated shapes and curves even it may needed to five axis CNC machine [25]. (Mentioned before) This way is look like direct way of impeller machining; the CAD data transferred to machine and pattern is produced. It is even, electro discharge machining and welding or mixes of them can be applicable if the pattern material were metallic.

2.3.3 Welding or some other joining procedure

In some cases, the shape of impeller is complicated and dependently the material, which will be used, and the available facilities manufacturer innovates some mixed method to produce impeller. Welding and brazing is used in some cases to joining the vanes to the shroud part of impeller. Figure 15 shows Impeller manufactured via welding procedure. Sometimes look like machining procedure it need to costly CNC welding machine. Benefit of this method is low cost and time compare to machining method, also have limitation such as applicability in narrow and shapeable plates and weld able materials [26]. Moreover it involves some problems and restriction of welding procedure such as corrosion and erosion.

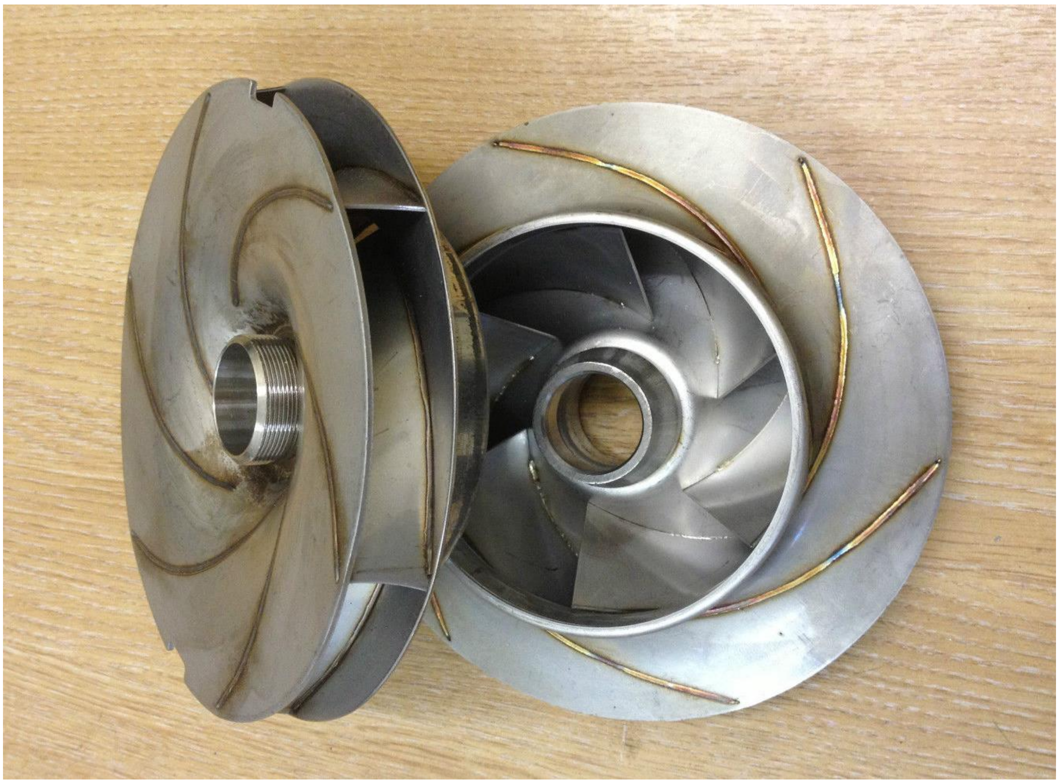


Figure 17: Impeller manufactured via welding procedure

2.4 Rapid prototyping and rapid tooling

In this section another method to producing pattern have been investigated which is easiest and included so low cost to other mentioned method. Using rapid prototyping to making pattern is the issues which are implemented via most pump manufacturer. As it mentioned in previous section in this way model is prepared layer by layer which thickness of layer can be just several micron and because of this feature producing the most complicated curves and shapes is possible [27].

This way is an innovative way to access product before mass production and the product are be testable before mass production, also make desired changes very easily. Compare to other method, the cost of changing and improvement of segment is too low and more over it saves more time and accelerate speed of manufacturing procedure. in case of pattern manufacturing some times because of the curves it need to pattern be slice by slice to be extract easily from core box and because of this, core boxes produced in several stages [27, 28]. Before casting pattern segments montage on top together to be, accommodate inside of core box. To have such a pattern, manufacturer may produce it part by part and then montage together or it may produce like bulk and then sheared it to parts. If the pattern were metallic it need to precious cutting which can be done via wire cut machine or in some cases laser cutting implemented. Some difficulties subsequently are inherently in cutting procedure, to avoid this problems, the ability to producing layer by layer would also be so helpful. It is one of the other reasons which leans manufacturer to implemented RP in pattern manufacturing to use layer by layer feature of this technique [29].

Utilizing RP technology in impeller manufacturing, most of the time is indirect way. Manufacturer interests are abilities of this technology in reverse engineering of impeller. In reverse engineering procedure, CAD data have to be prepared initially. These data obtains via scanning the impeller. The scanned data transferred to CAD software and after analyzing, are transferred to RP machine and the primary pattern will be produced based on these data. Then this pattern will be used to producing main casting pattern[24].

RP method is also applicable directly. In a way CAD data of impeller prepared by designer and then this data transferred to RP machine and first model is produced layer by layer. This model look like reverse engineering method is applicable to produce casting pattern. Most of the time the material which is used is not rigid enough and doesn't have expected erosion resistance so it wouldn't be able to use directly as an impeller or even casting pattern. Briefly, the benefit of this way is rapid and agile ability to access touchable model before mass production.

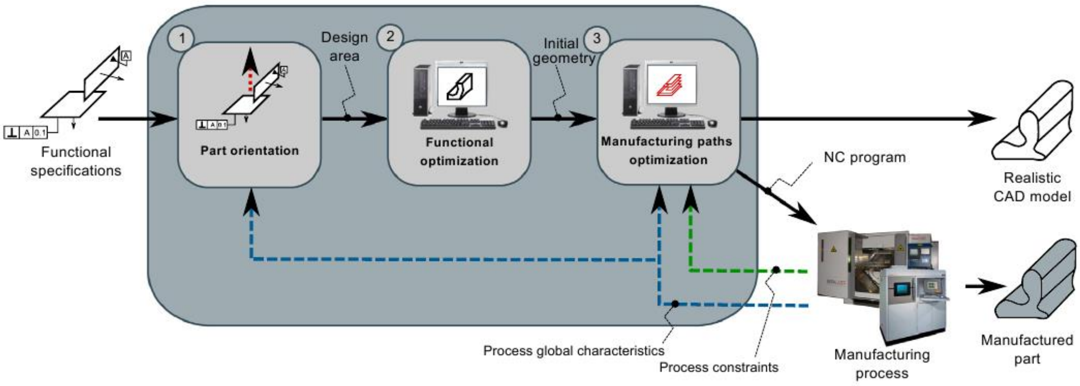


Figure 18: Rapid proto typing procedure (Ponche et al., 2014)

In this thesis, rapid proto typing method to producing pump impeller and other benefit, which would obtain via implementing this method, has been studied. Figure 17 is schematic view of RP procedure.

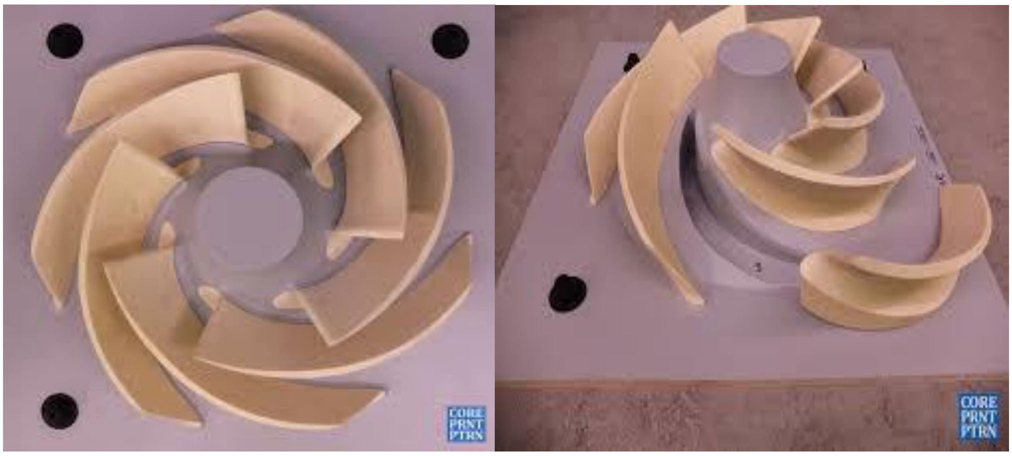


Figure18: Primary pattern of impeller produced by RP machine (Ponche et al., 2014)

As it recognizable in figure impeller molding is look like every part need to one plate in advance to put the core parts on it. Core parts like figure 18 can be separate and after molding procedure it will extract to core box be ready for pouring molten metal.

Chapter 3

IMPELLER MANUFACTURING

3.1 Introduction

The main challenging issues in pump industry are design and manufacturing of the complex shape parts. Mechanical construction of impeller is determining the specific features of every pump. head and flow rate mostly depended on impeller construction, so design and manufacturing issue in this regard would be so significant in case of optimizing the efficient parameters [16].Also re-engineering and engineering concept are one of the proposed ways by manufacturer in regards of production costs and time optimization [3].

This chapter will be highlights reverse engineering and manufacturing processes of centrifugal pumps impeller. Here reverse engineering of specific pump impeller will be investigated. Two general methods consist of conventional method and CAD/CAM method will be discussed briefly and Rapid prototyping method as objective of this thesis will be clarify completely. The main challenge in this regard is procedure of reverse impeller manufacturing which is consisting of reverse blade manufacturing. The production method will be use after blade manufacturing is casting method and the constructed blades will be used as part of core box to producing core, which will be implemented in impeller casting. The advantage and disadvantage of impeller casting discussed in previous chapter. In addition, the mentioned methods in this regard will be compared with two other methods and Rapid prototyping method. Via implementing RP methods the other desired features such as surface quality and dimensional accuracy is improved in parallel with production costs and time reduction.

3.2 impeller manufacturing with considering blade shapes

In regard of manufacturing procedure, the desired parameters in virtual area in some cases are not coincident with real parameters. So it need to manufacture a model of designed part to execute the experimentally tests on it. That is compulsory in manufacturing cycle of every production and impellers also are not exception. There are so many methods to manufacturing the initial model of impellers, such as CNC machining, rapid prototyping and even in some cases it produced manually via model manufacturer[20]. In next steps we would have glance of view about the initial model manufacturing and analyze the final method of impeller production.

Before the investigation of impeller manufacturing process it would be better to have glance of view about the pump impeller shapes. As mentioned in previous chapter that pump impellers from the shape points on view might be classified as a) open impellers and close impellers. Each of these groups depend blade shape might categorized as 2D blind and 3D blind. Briefly there exist four different types of impellers as following:

1. 2D blade open impeller
2. 3D blade open impeller
3. 2D blade close impeller
4. 3D blade close impeller

Figure 19, 20 and 21 demonstrates some examples of these impellers

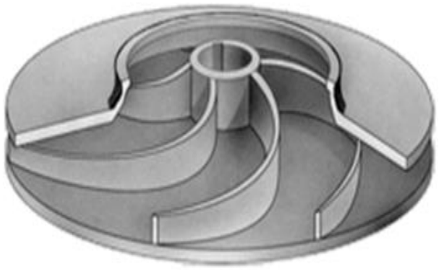


Figure 19: 2D blade open impeller   Figure 20: 2D blade close impeller

Figure 21: 3D blade open impeller

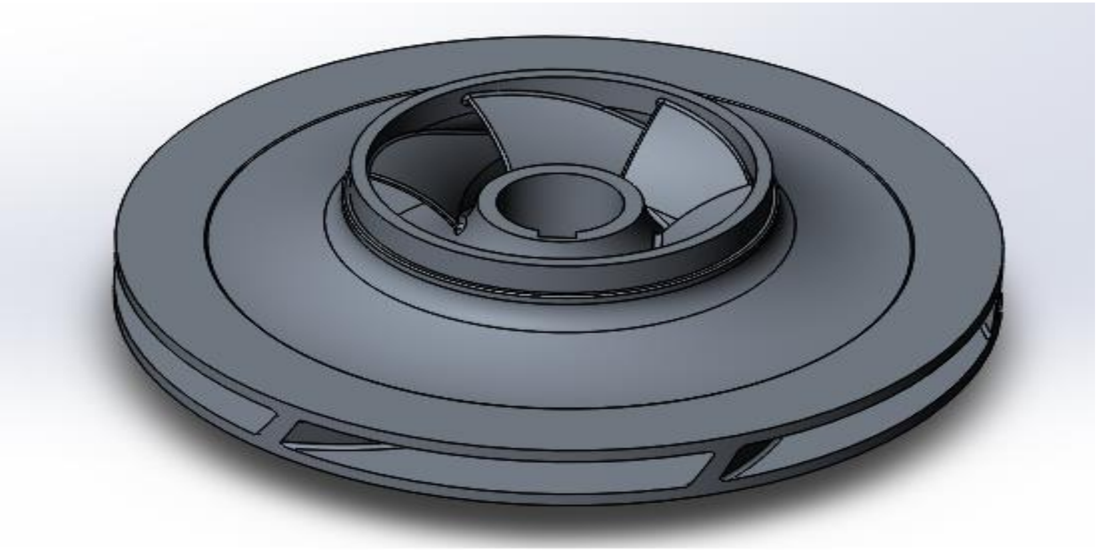


Figure 22: 3D blade close impeller

As it is mentioned in previous section there exist many manufacturing methods for direct or indirect production of the pump impellers, however popularity of sand casting method motivates the authors to employee sand casting as mass production method for impeller production. The main challenging issues in this way are” Core box” and “core” production [30]. Since the external shape (core box) for all type of impeller approximately is similar and also needs simple manufacturing processes (i.e. machining process) for production, core production is out of the author interest to consider in this thesis. Here in this thesis we are going to consider two common methods, also we will introduce our new method (Using RP) for manufacturing core box which will be used in sand casting process. These three methods are as following:

1. Machining (CAD/CAM)
2. Conventional method
3. Rapid prototyping

It needed to mention this fact which open impeller producing is so easy and simple compare to closed impeller especially in case of reverse engineering. Because all the points and curves are conveniently accessible, But at the close impeller it a bit hard and complicated. This complexity forced and impelled Manufacturer to find and invent particular and stringent ways in case of closed impeller reverse engineering. One of the most popular methods in this case is use of 3D scanning and subsequently 3D printing which spaciously would investigate in this thesis.

Glance of view about the manufacturing classification

- 2D and open impeller reverse engineering have the easiest procedure in reverse engineering which the core box maker can use the impeller itself as a casting core box (Figure 22) and make sand or other model.

Figure 23: This impeller can use as core box directly

- 2D and closed impeller become a bit harder. In this case manufacturer removes one wall side of impeller via cutting and makes the core box just like the previous one. Figure 23 – 30 are demonstrating all shapes of impellers in case of core box manufacturing.

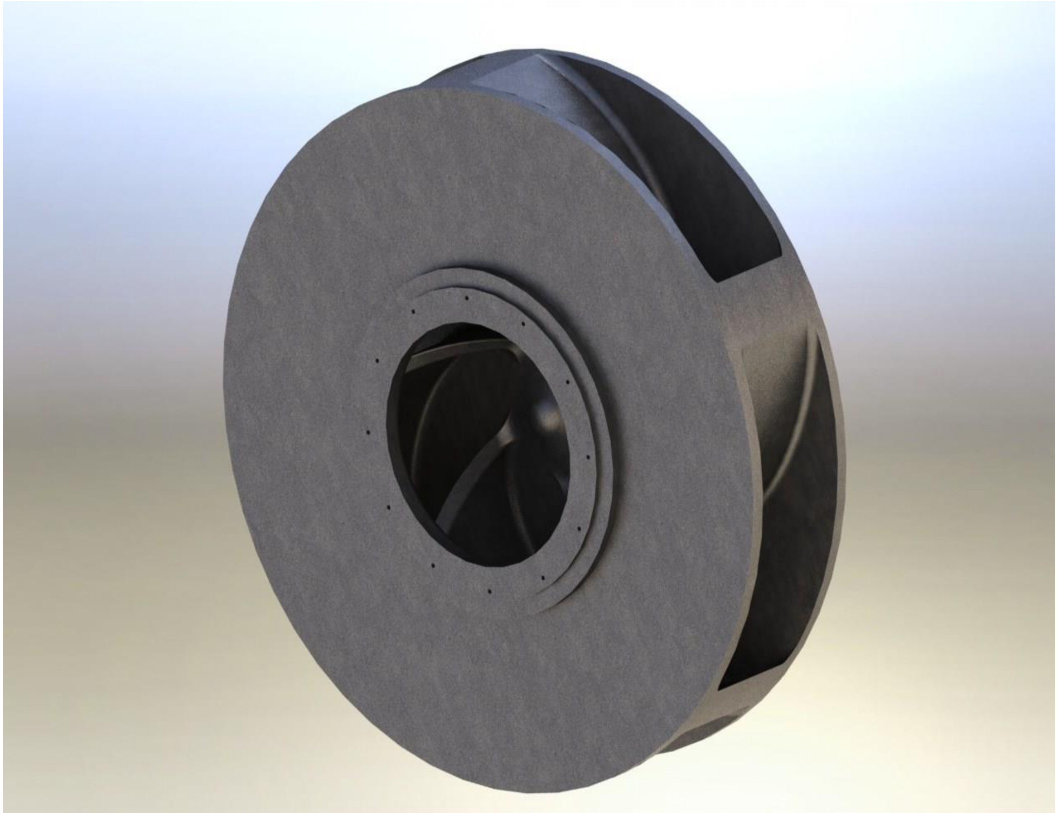


Figure 23: Normal 2D and closed impeller

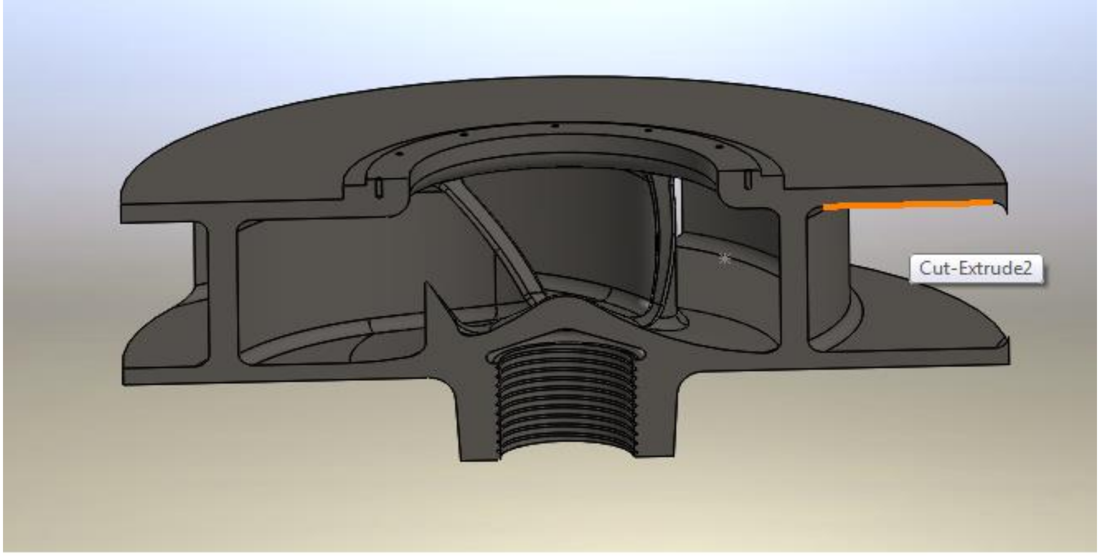


Figure 24: Diametric cut just to have better inside view

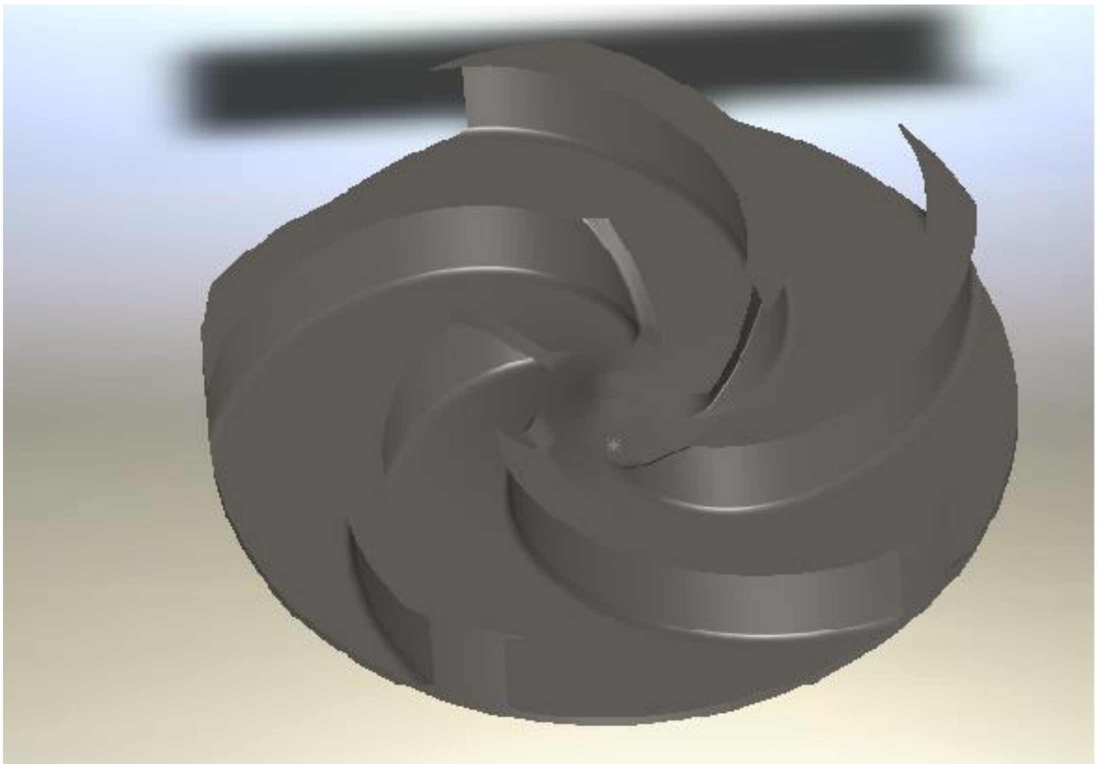


Figure 25: Top surface is removed and it can usable to making core box directly

Figure 26: Produced core via using 2D impeller directly as a core box

- 3D and open impellers are like to the 2D and open one. Modeling and core box making is also the same.

Figure 27: Open and 3D impeller

- 3D and closed impeller. The most complicated case to manufacturing.

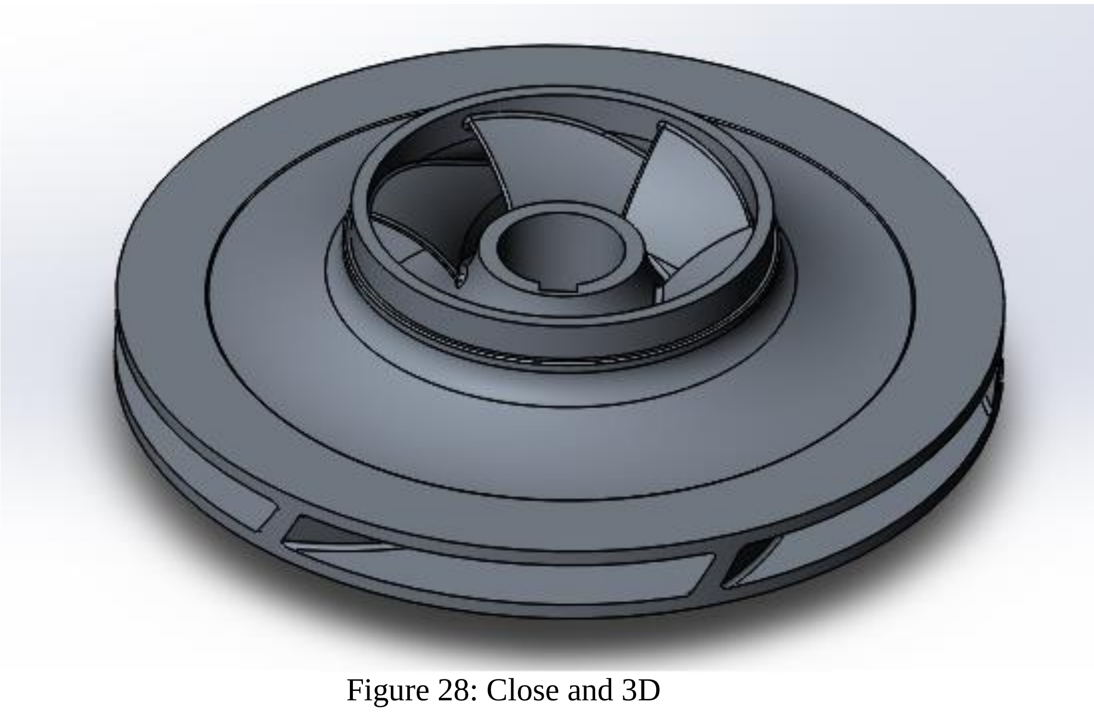


Figure 28: Close and 3D

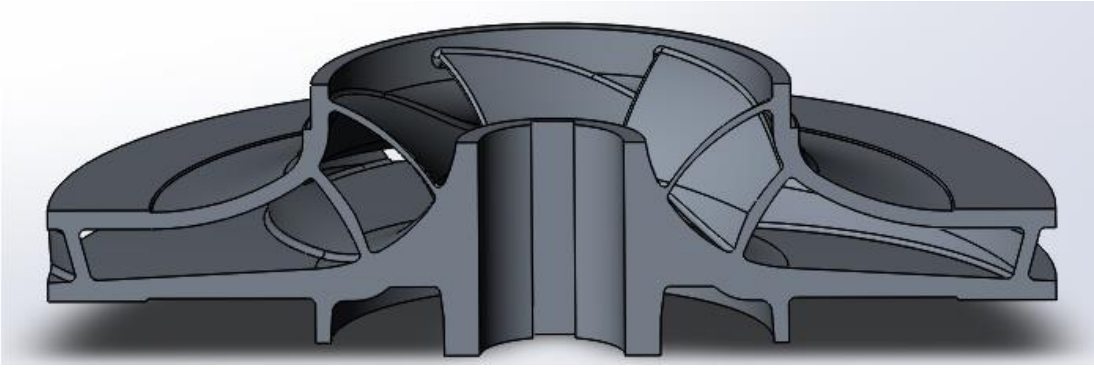


Figure 29: Diametric cut to have better view inside

The main focus of this thesis is on the last part (3D blade and close impeller).

In this case, conventional method just like 2D and closed impeller is applicable too, but it is a bit difficult and cost of this operation is so much. Because removing and cutting the wall need to high precious cutting machine such as CNC wire cut.

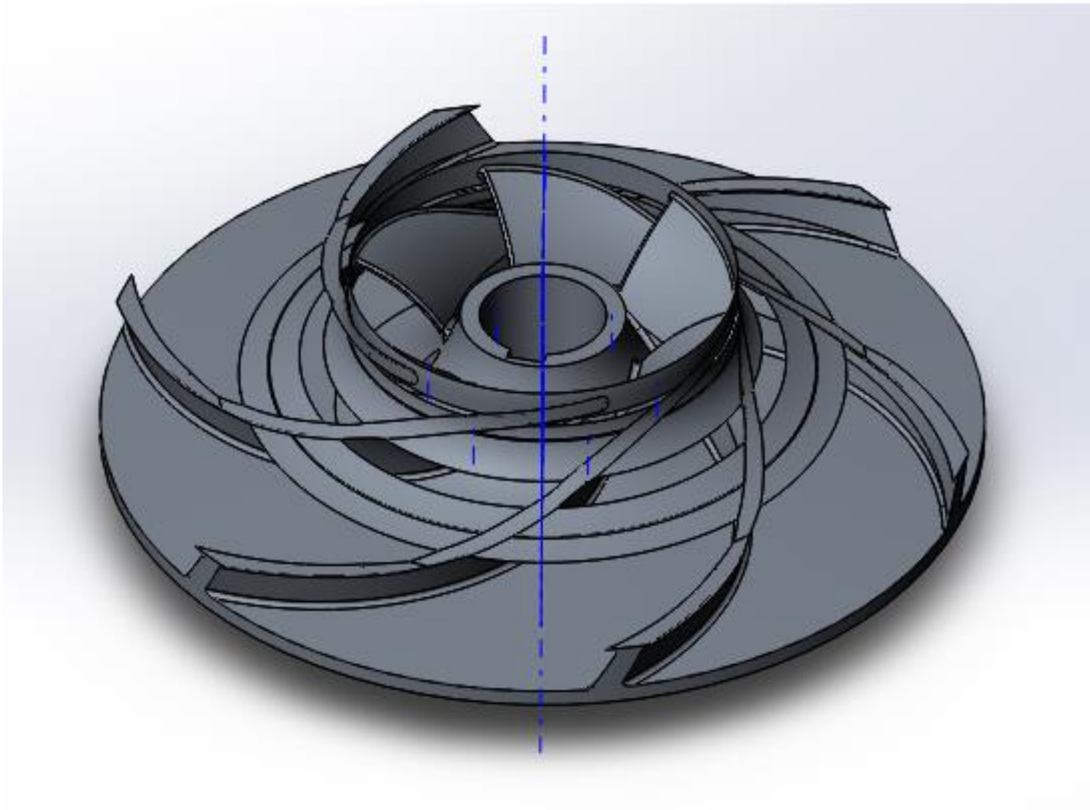


Figure30: Top surface is removed. It is applicable via high precision cutting machine such as CNC wire cut. It is ready to making core box

Before the addressing and investigating last impeller shape manufacturing (3D and close), it would be better to have a glimpses toward to all the general ways in reverse engineering and investigate and compare with together in case of impeller manufacturing.

There are three common methods in reverse engineering of pump impellers [31].

- CAD/CAM
- Conventional method
- Rapid prototyping

3.3 Impeller manufacturing using machining process (CAD/CAM)

To achieve the minimum time in product development procedure and making competiveness in production, computer aided design (CAD) and followed computer aided manufacturing (CAM) are applied in manufacturing procedure. In this regard computer numerical control (CNC) machines entered in the competitive area in case of impeller machining. CNC machines can apply in two different areas, direct and indirect manufacturing .direct manufacturing is applicable in open impeller, both in 2D and 3D shape. It is because of the limitation in tool accessing in blind part of impeller. In case of 2D and open impeller 3axis CNC machines are applicable and there is no need to 5axis machines.(Figure 31) It needs to mention that 5axis machines are so costly compare to 3D ones [25].

In 3D shape impeller it has to 5axis machines be used. These machines are mostly used in turbine impeller and aerospace industry and special dies. These parts like 3D impellers have complex geometry and surface complexity so 3axis are not applicable. In fact, the centrifuge impellers are the perfect expression of competent design and manufacturing abilities of 5axis machining.

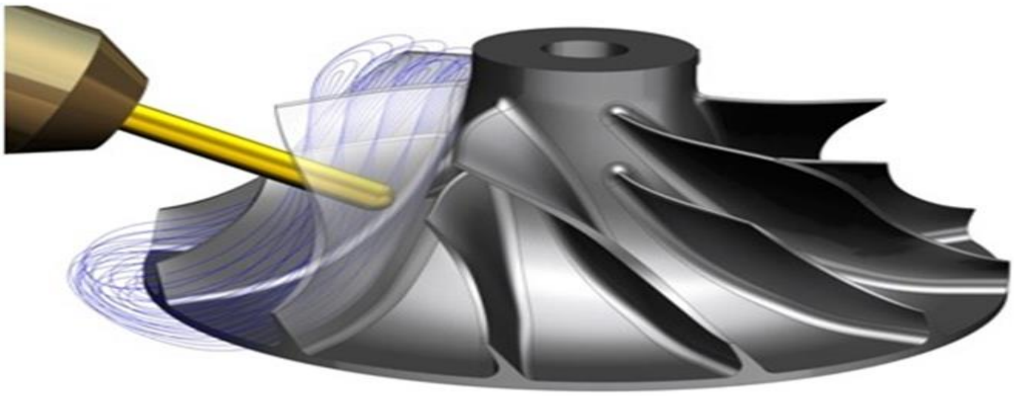


Figure 31: Direct 3D open impeller machining via 5axis CNC machine [25]

Figure 32 presents the procedure steps as direct manufacturing of impeller via machining process.

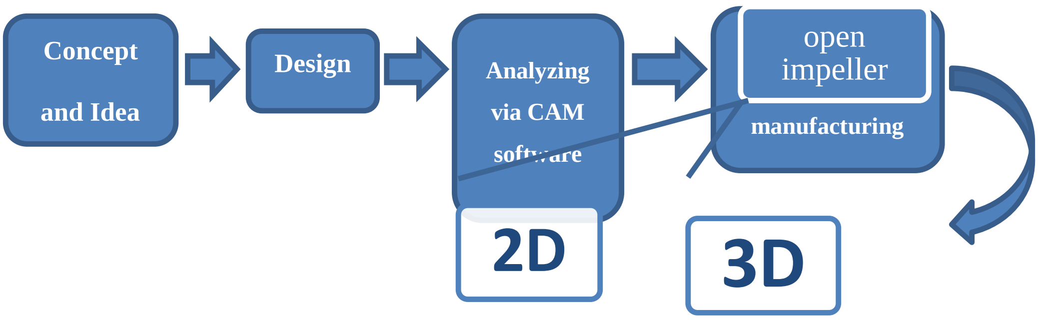


Figure 32: Direct manufacturing

Indirect manufacturing itself can be applicable in two different sections. Use to making casting core box which comes from design section, and the next method which is also used to making casting core box but in case of reverse engineering. Indirect method widely used as case of reverse engineering, Both In case of open 2D or 3D impellers as it obvious in the figure 32.

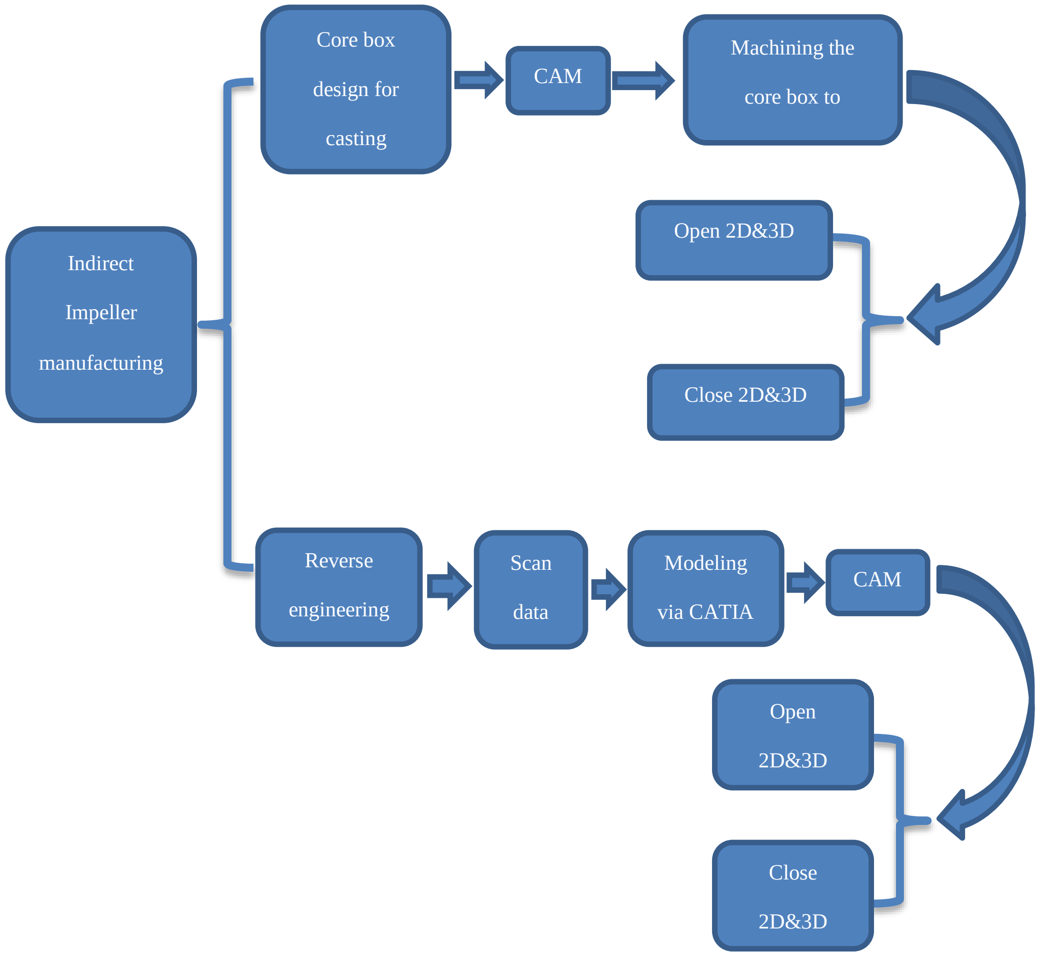


Figure 32: indirect manufacturing

As it mentioned before directly machining is applicable, but the cost of this procedure is much higher than other method (in specified part we will discuss about the costs completely and will compare each of the methods with together). In addition to cost, we know that this way is implicated just for one impeller and that is so clear which producing more impeller will need more time. So leading time is one of the main factors which affect our procedure and same as costs will be investigated completely in separate parts.

Indirectly Applicants of CAD/CAM (machining) method to produce casting parts is also applicable in close 2D or 3D impellers. The procedure is similarly to conventional method, but the difference is that via using CAD/CAM the process of core box making would be more accurate. In this way which is absolutely applicable in 2D and 3D open or close impellers, firstly 3D scan of impeller is prepared, and then the scanned data transferred to CATIA software and accurate shape and dimension of impeller is prepared via this software. Tool path and other required data prepared and transferred to CNC machine. After machining the produced blades are usable to casting process just like conventional method. Hence the produced blades are metallic (most of the time are steel) so they are be usable as a direct core box to producing sand core (instead of aluminum part).

A centrifugal impeller is a perfect example of a part that can be efficiently designed and manufactured with the help of a computer. Machining these types of complex shapes requires a CAM system with a high degree of flexibility in tool orientation.

3.4 Impeller manufacturing using conventional sand casting process

In conventional method, manufacturer use casting procedure to produce impeller. It will be taking less cost compare to other methods but it has some other limitation, which compel manufacturer to select and try other methods depending the case, which they want to produce.

Such like other casting operation it need to main section such as die, core and core box. (This method completely investigated in chapter 2).

Main issue is producing core box to making core. For this reason in conventional method, model manufacturer cut one of the blades and use it as template to produce wooden or plastic initial blade. (presented in figure 33 and 34). Since the cut blade doesn’t have accurate dimension so it cannot be applied directly as core box blade and model manufacturer compel to produce accurate wooden or plastic one. This wooden blade will be used to producing core (sand core). Since the wooden core boxes are fragile and have less abrasive strength compare to aluminum one, manufacturer have to produce metallic core box. Therefore, this work is necessary especially in case of mass production. Now the produced sand core is useable to manufacturing the main and final aluminum core box. The accuracy in cutting procedure is one of the main factors, which would ensure the rest of the procedure. Every wrongness and in this section would be transferred to the rest of operation.

Figure 33: conventional core box making

Figure 34: Wooden blade is prepared to making core box

That is the traditional core box making method. In this way, the wooden or plastic core box produced by hand via professional model maker. These initial blades are used to making sand core. In this regard, aluminum core box will be casted via this wooden core box and prepared to make main core to use for final casting of impeller.Mentioned method is old and traditional method in reverse engineering of impeller and it is to keeping being not more used method. Because most of the work is done by hand and actually, the mistake of labor transferred to work piece so it wouldn’t be so accurate and dependable. But as advantage of this method the cost issue is so lower than compare to another method and it has also done in some traditional workshops [20]. Procedure is presented in figure 35.

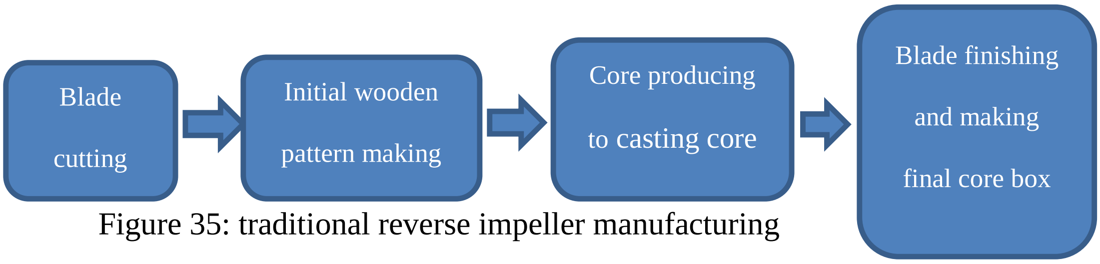


Figure 35: traditional reverse impeller manufacturing

Chapter 4

IMPELLER MANUFACTURING USING RP AND SAND CASTING PROCEDURE

4.1 Introduction

In order to development a new product it is invariably necessary to produce a single prototype of a designed product or system before allocating of a large amount of money to new production facilities or assembly lines. The cost is very high and production tooling takes considerable time to prepare [27].

Consequently, a working prototype is needed to design evaluation and to suggest problem solutions before a complex product and system are introduced. The technology, which considerably speeds the iterative product development process, is the concept and practice of Rapid Prototyping (RP) also called Solid Freeform Fabrication (SFF) [27, 28, 32, 33].

Initiated in the mid-1980s. The advantages of this technology include the following:

• Physical models of parts produced from CAD data files can be manufactured in a very short time and allow the rapid evaluation of manufacturability and design effectiveness. In this way, Rapid Prototyping serves as an important tool for visualization and for concept verification.

• With suitable materials, the prototype can be used in subsequent

• Manufacturing operations to produce the final parts, in this way Rapid Prototyping serves as an important manufacturing technology.

• Rapid Prototyping operations can be used in some applications to produce real tooling for manufacturing operations (Rapid Tooling). In this way, it is possible to obtain tooling in few days. [34]

4.2 Implementing Rapid Prototyping (RP) Technology

In case of impeller manufacturing using RP, the initial phase of this procedure is exactly the same as CAD/CAM method. Scanned data prepared and transferred to CATIA software, after analyzing and refining the data it transferred to 3D printing machine and 3D blade is produced. Now this segment is prepared to be used as an initial pattern to produce final core box. Since the segment is made by plastic powder in order to prevent abrasion, thus, making the aluminum core box is unavoidable.

Now, the prepared aluminum core box is usable as core in casting process.

The summarization of Rapid prototyping technology has been illustrated more in details regarding of advantages and drawbacks of procedure in previous chapter, accordingly.

Now implemented procedure is obtained as below:

First the impeller has to be cut diametrically and then it has to be machined to reach the soft and accurate surface to get the point via 3D scanner.in next figure shows the cut and machined impeller. In the figure 39 the cut impeller section for 3D scanner is shown.

Figure 36: Cut Impeller Ready to Scan

After the cut impeller had scanned, the data transferred to CATIA software in order to analyze and make appropriate data for RP machine. Figure 31 show the scanned data preparing and analyzing from 3D scanner in the Catia software.

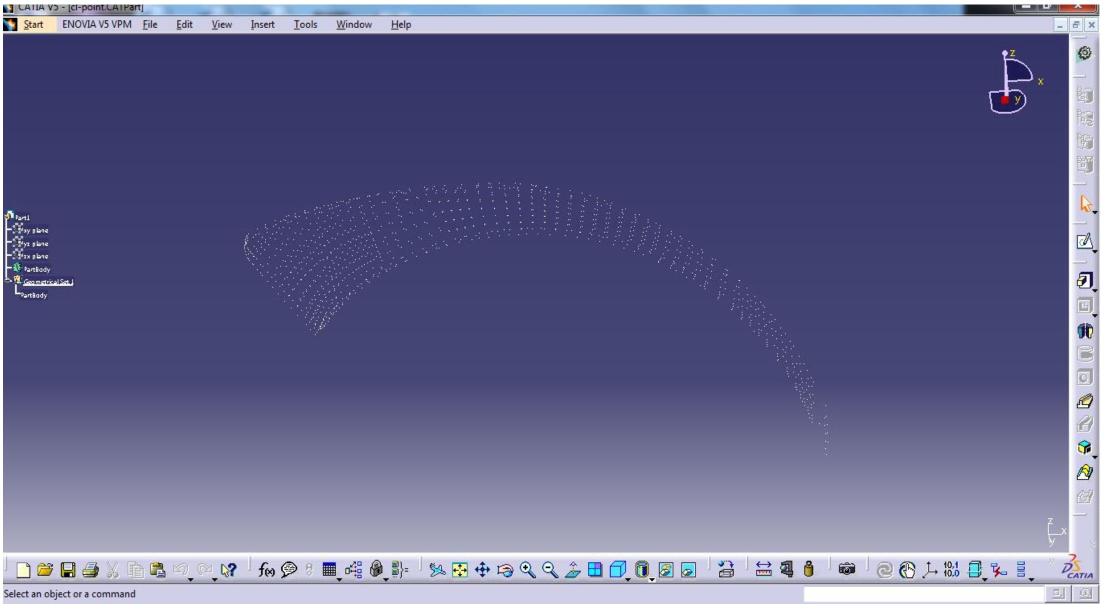


Figure 37: Scanned Data Preparing and Analyzing

CATIA software has the ability to recognize the scanned data. It enables us to draw 3D model of impeller just like the part design. So it would enable us to have any change and improvement in this section.

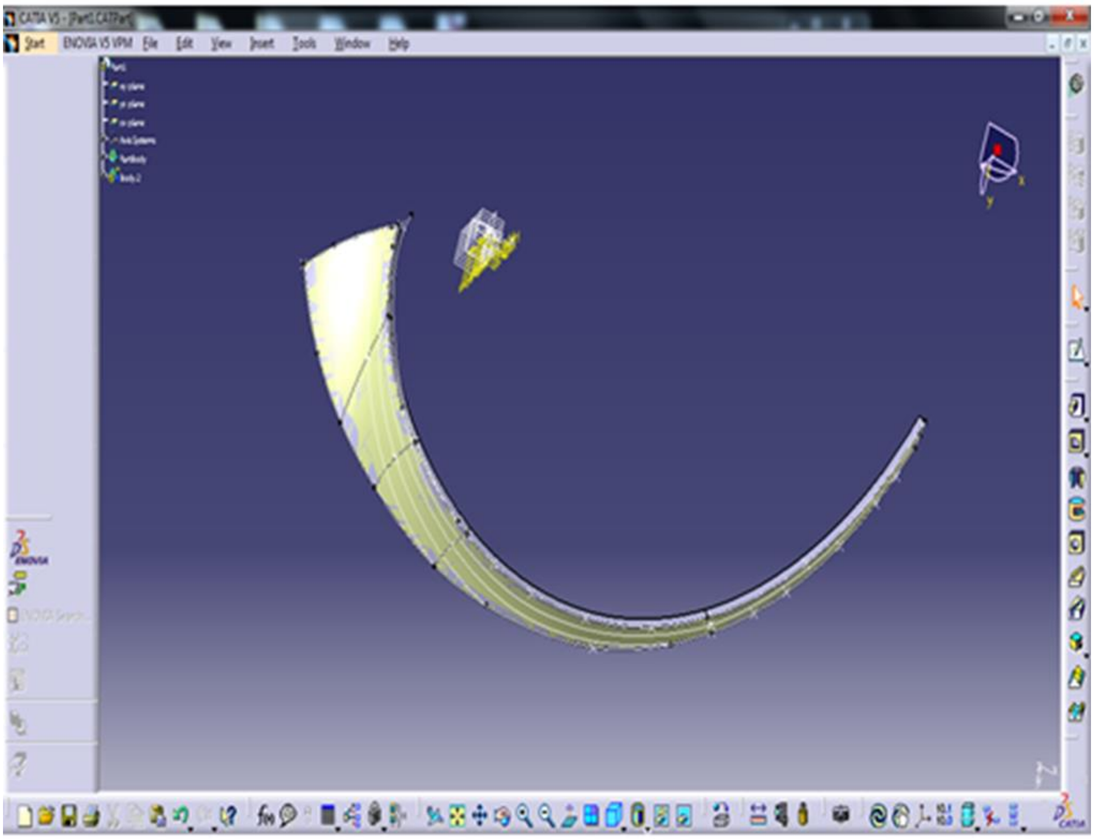


Figure 38: CATIA Software Enables us to Implement Any Changes and Improvement.

After data analyze, and drawing 3D shape of impeller it is ready to transfer to RP machine, machine receive the data and produce initial model of impeller layer by layer.

Figure 39: Blade of Prototyped Impeller Via 3D Printing Machine

After preparing prototyped blade, then it is ready to be used in initial core box construction in order to produce casting aluminum blades. Figure 33 show blade of prototyped impeller via 3D printing. As it has been mentioned before, making aluminum core box is inevitably since the prototyped blade is not rigid enough to use as a main core box and it is damaged and eroded so easily.

Figure 40: This Prototyped Blade will be used to Produce Aluminum Blade which are used Inside of Core Box

The produced blades have to be prepared with high surface quality and also extra flasher has to be removed. This work has done accurately via die manufacturer

Next figure shows the prepared aluminum core box. The finished blades joint to shroud part of impeller and finally are used as core box to make sand core.

Figure 40: The Blades Prepared and Joined to Main Core Box via small pins which Located in down side of impeller shroud

Casting technology has been observed and evaluated in order to produce model and core box for our case study. Figure 35 show The Blades Prepared and Joined to Main Core Box via small pins, which Located in down side of impeller shroud (Making core box and core via using RP 3D printing machine).

After the aluminum core box has been prepared and also, dimensional control has checked, now, it is ready to produce the sand core of impeller by foundry experts. Special sand is mixed properly with particular glue and poured inside of core box then CO2 gas is injected to inside of Die for solidification purposes. Figure 36 Prepared Sand Core via using Aluminum blades.

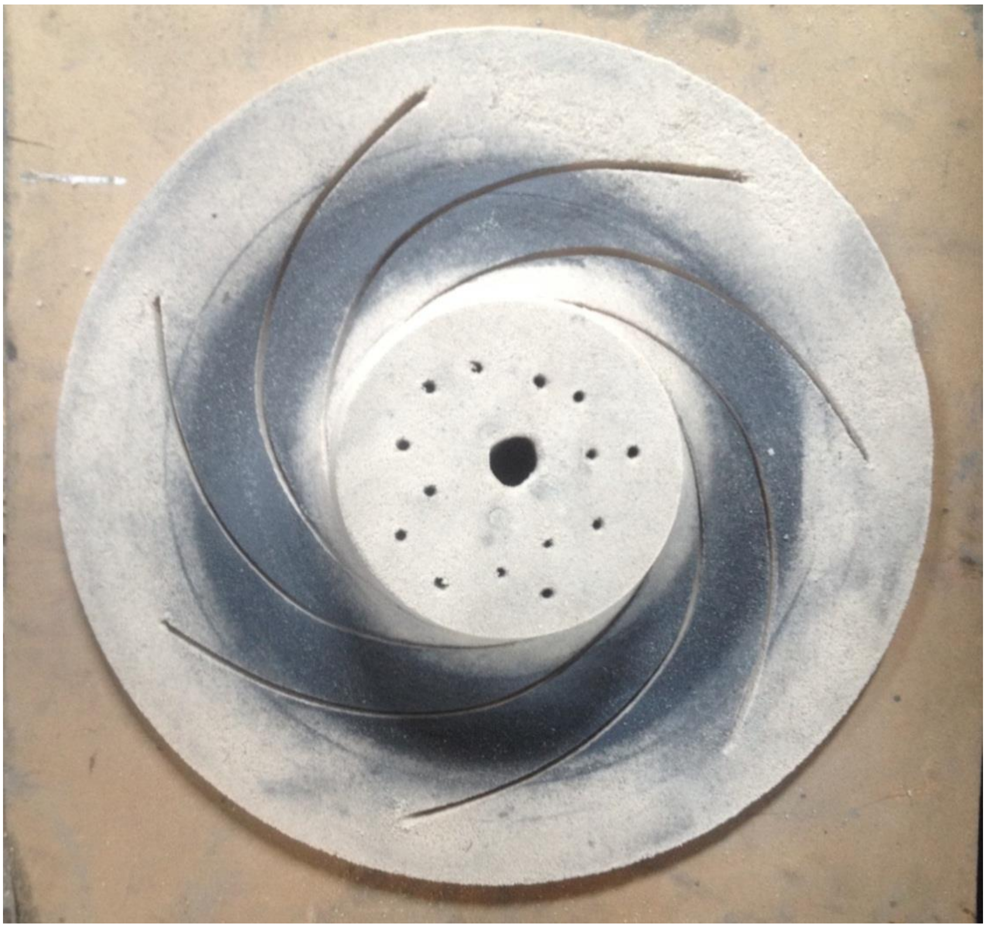


Figure 42: Prepared Sand Core via using Aluminum blades

This sand core accommodated inside of die among up and down parts. Next figures shows the down part of die (which produce the shroud of impeller) and sand core montaged on top of it. Figure 37 illustrated the down part of die.

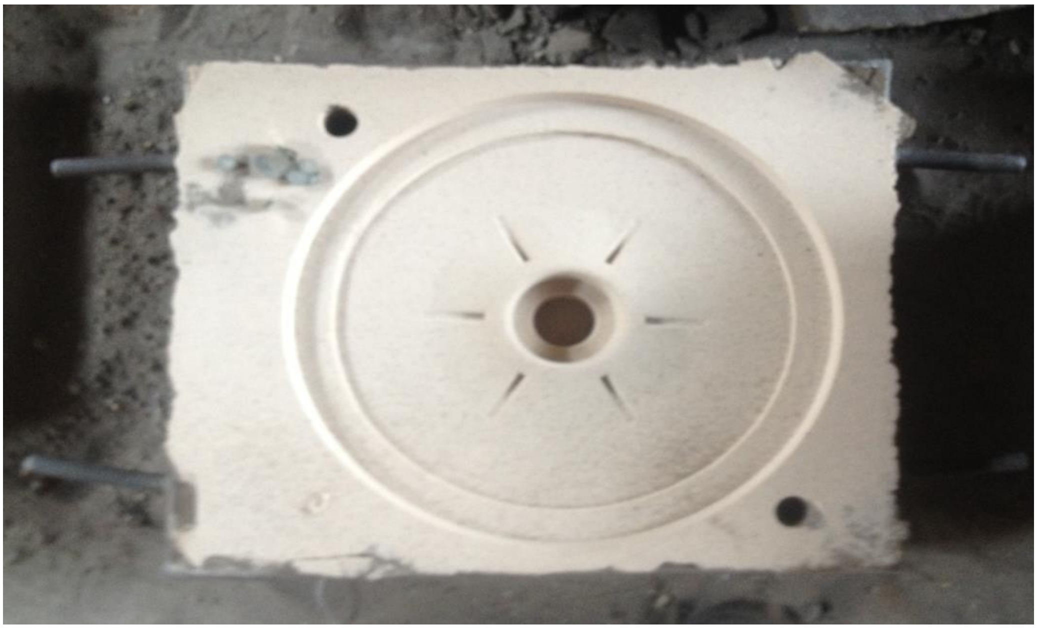


Figure 43: Down part of die

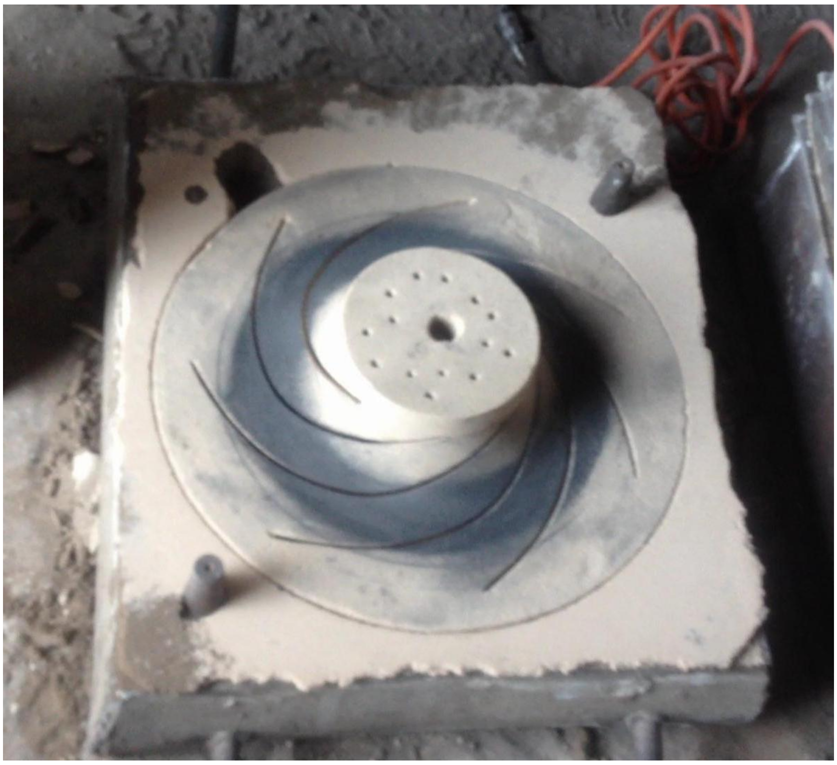


Figure 44: Sand Core is Accommodate on Top of Down part

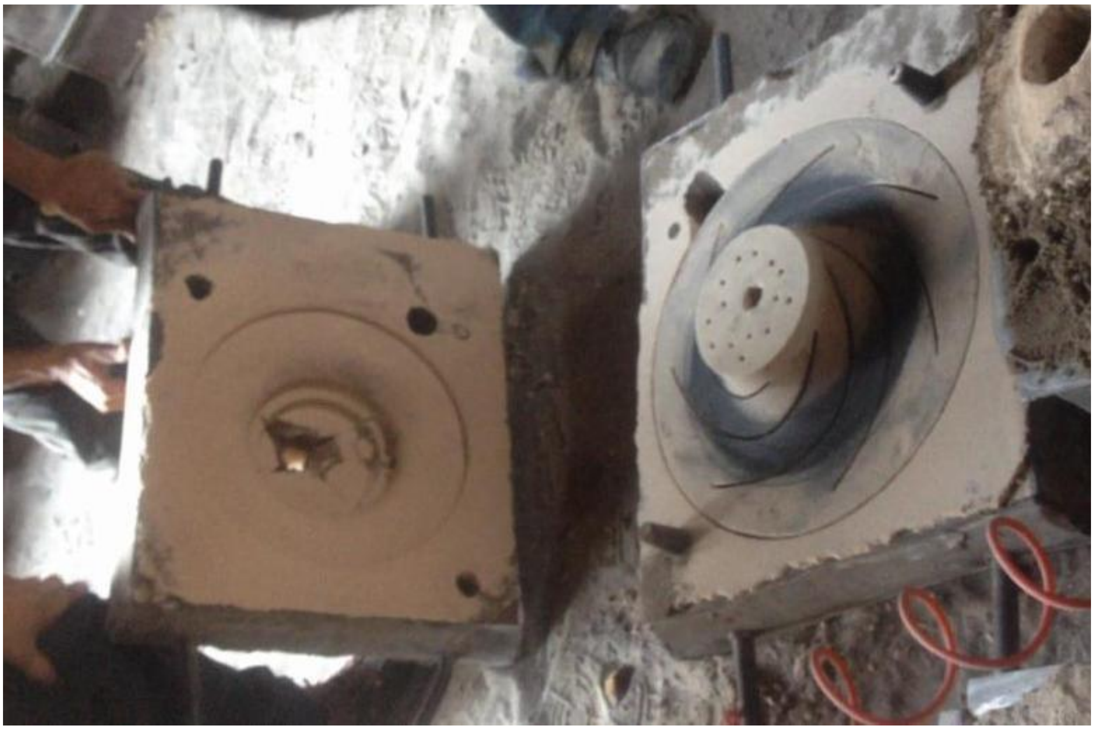


Figure 45: Down Part, Sand core and top part are ready to montage

Figure 46: Montaged Die and it is Ready to Pour the molten material.

Die parts are checked in order to fit properly on each other. Subsequently molten cast iron is poured inside the die via refiner and then waits to cold down the molten material. In some cases it takes longer time (half day). The casing method from die to cast is shown in figure 40.39, 38. Depending on thickness of sand part and dimension of work piece and material it can be variable.

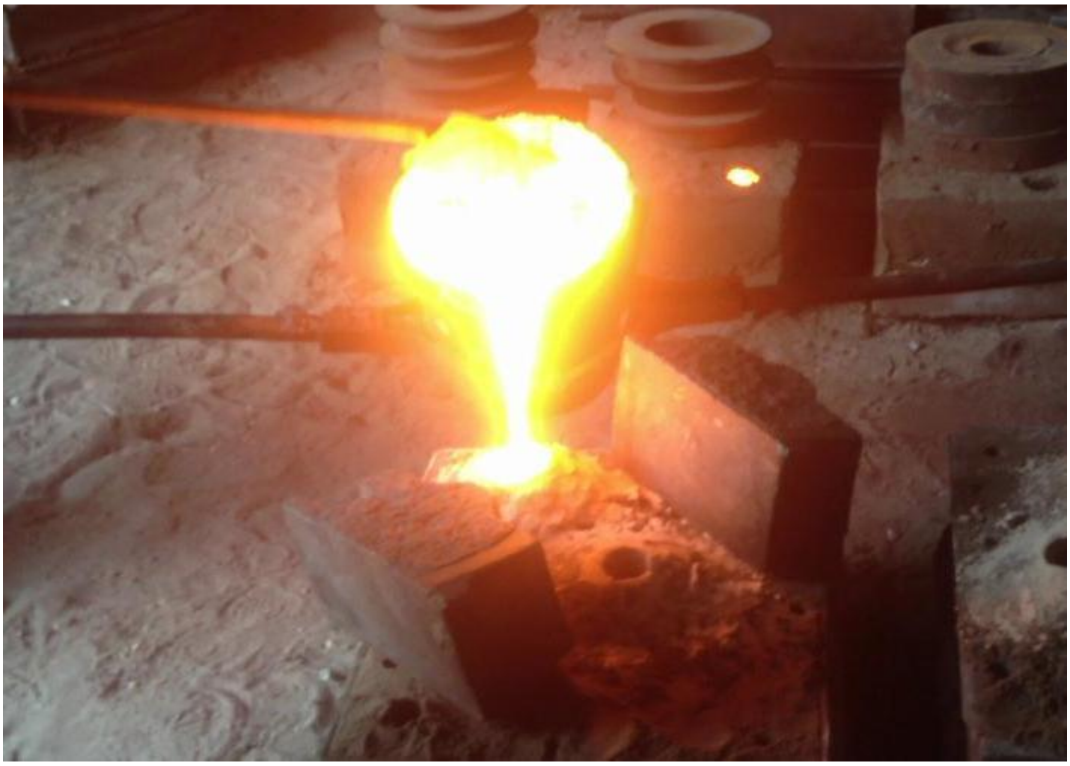


Figure 47: filling the die with melted cast iron

Chapter 5

ANALYSIS AND RESULTS

5.1 Analysis and results

In this chapter, manufacturing procedure of different kinds of pump impellers compared with together as time and cost point of view. For cooperation, group technology (GT) cast analysis based on code generation used. According to GT methods and category, of pump, code generation was clear and is started 3 digit from 111 to 555. All the details collected in one table. After that, the result of hydraulic test in two impellers manufactured with different methods will analyzed and the results will be presented in diagrams.

Data gathering is related to Tabriz Industrial Town (North – West industrial city of Iran) with consulting experienced Pump manufacturer in last 6 month. Normal work day supposed 10 net hours per a day.

5.1.1 Total Cost calculation procedure

The mathematical formula for Total Cost (TC) calculation in impeller manufacturing procedure is obtainable by sum of Total Technical Work Force Cost this formula according to the impeller calcification was divided in three parts namely: Total instrument Cost, Total Material Cost, and Total technical work force. Fig 46 shown this three component of TC. Formula 1 illustrated the mathematic formula of TC.

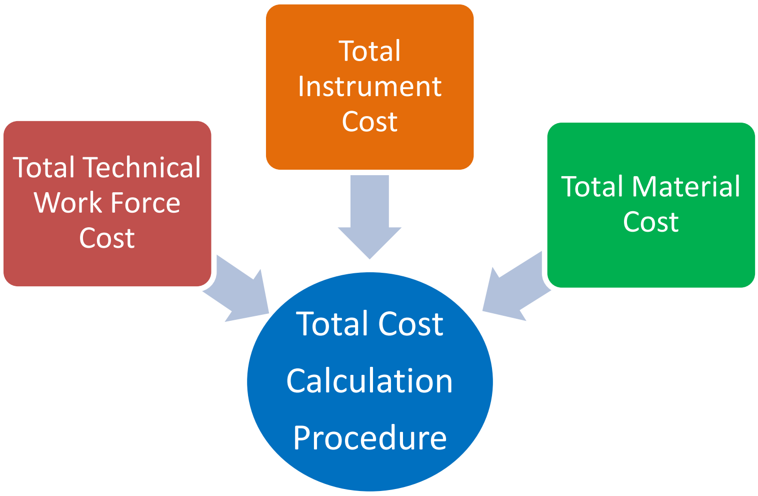


Figure 48: Total cost Calculation procedure

$$\sum C = \sum C_{tw} + \sum C_{i} + \sum C_{m} \qquad (5.1)$$

$\sum C$: Total procedure Cost

$\sum C_{tw}$: Total Technical Work Force Cost

$\sum C_{i}$: Total Instrument Cost

$\sum C_{m}$: Total Material Cost

The second formal of TC illustrated in equation 2 based on the three diagram of classification impeller the index of n show the manufacturing methods consist of 1= conventional method, 2= machining method and 3= RP method. The index of m show the procedure sequence and the index of P show the sub procedure costs.

$$\sum C = \sum dC_{nmp} \text{ or } \sum IC_{nmp} \qquad (5.2)$$

dC_{nmp}: direct Impeller manufacturing cost

IC_{nmp}: Indirect (reverse) manufacturing cost n: manufacturing method (1: conventional method, 2: machining method, 3: RP method)

m: procedure sequence (1: design, 2: pattern manufacturing, etc. variable in each method)

p: sub procedure costs (1: technical work force, 2: instruments, 3: material)

For example, dC_{311} related to direct, RP method, design, technical work force cost.

5.1.1.1 Procedure detail for direct impeller manufacturing

The code generation based on the classification of the impeller was defined in the above. It was started from conventional method until RP method in the between direct and indirect manufacture.

1) Conventional method

1) Design (1: Technical work force, 2: Instrument)
2) Manually pattern manufacturing (1: Technical work force, 2: Instrument)
3) Foundry (1: Technical work force, 2: Instrument, 3:Material)
4) Final machining (1: Technical work force, 2: Instrument)

2) Impeller machining

1) Design (CAD/CAM data) (1: Technical work force, 2: Instrument)
2) Pattern machining (1: Technical work force, 2: Instrument, 3:Material)
3) Foundry (1: Technical work force, 2: Instrument, 3:Material)
4) Final machining (1: Technical work force, 2: Instrument)

3) Impeller manufacturing utilizing RP technology

1) Design (1: Technical work force, 2: Instrument)
2) Pattern manufacturing utilizing RP technology (1:Technical work force, 2: Instrument)
3) Foundry (1: Technical work force, 2: Instrument, 3:Material)
4) Final machining (1: Technical work force, 2: Instrument)

5.1.1.2 Procedure detail for Indirect (reverse) impeller manufacturing:

1) Conventional method

1) Impeller cut(1: Technical work force, 2: Instrument)
2) Manually pattern manufacturing (1: Technical work force, 2: Instrument)
3) Foundry (1: Technical work force, 2: Instrument, 3:Material)
4) Final machining (1: Technical work force, 2: Instrument)

2) Impeller machining

1) Impeller cut (1: Technical work force, 2: Instrument)
2) 3D scan (1: Technical work force, 2: Instrument, 3:Material)
3) Data analyzing and CAM (1:Technical work force, 2: Instrument, 3:Material)
4) Foundry (1: Technical work force, 2: Instrument, 3:Material)
5) Final machining (1: Technical work force, 2: Instrument)

3) Impeller manufacturing utilizing RP technology

1) Impeller cut (1: Technical work force, 2: Instrument)
2) 3D scan (1: Technical work force, 2: Instrument, 3:Material)
3) Data analyzing (1: Technical work force, 2: Instrument, 3:Material)

4) Pattern manufacturing utilizing RP technology (1: Technical work force, 2: Instrument)
5) Foundry (1: Technical work force, 2: Instrument, 3:Material)
6) Final machining (1: Technical work force, 2: Instrument)

For clarity of this method, some examples for TC calculation was used. Frist one TC calculation for Direct and close 3D impeller manufacturing with RP method defined in the above equation.

$$\sum C = \sum dC_{nmp} = \sum C_{tw} + \sum C_{i} + \sum C_{m} \quad (5.1)$$

$\sum C_{tw} = \sum dC_{311} + dC_{321} + dC_{331} + dC_{341} = \sum 1800 + 800 + 800 + 200 = 3600$

$\sum C_{i} = \sum dC_{312} + dC_{322} + dC_{332} + dC_{342} = \sum 350 + 1100 + 1000 + 150 = 2600$

$\sum C_{m} = \sum dC_{333} = 90$

$\sum C = 3600 + 2600 + 90 = 6290$

Example for Indirect and close 3D with RP method for TC calculation

$$\sum C = \sum IC_{nmp} = \sum C_{tw} + \sum C_{i} + \sum C_{m}$$

$\sum C_{tw} = \sum IC_{311} + IC_{321} + IC_{331} + IC_{341} + IC_{351} + IC_{361} = 100 + 150 + 100 + 800 + 750 + 200 = 2100$

$\sum C_{i} = \sum IC_{312} + IC_{322} + IC_{332} + IC_{342} + IC_{352} + IC_{362} = 40 + 200 + 100 + 1100 + 1100 + 150 = 2690$

$\sum C_{m} = \sum IC_{353} = 90$

$\sum C = 2200 + 2690 + 90 = 4880$

Or

$\sum IC_{nmp} = IC_{311} + IC_{312} + IC_{321} + IC_{322} + IC_{331} + IC_{332} + IC_{341} + IC_{342} + IC_{351} + IC_{352} + IC_{353} + IC_{361} + IC_{362} = 100 + 40 + 150 + 200 + 100 + 100 + 800 + 1100 + 750 + 1100 + 90 + 200 + 150 = 4880$

Direct and open 2D (machining method):

$\sum dC_{nmp} = dC_{211} + dC_{212} + dC_{221} + dC_{222} + dC_{223} + dC_{231} + dC_{232} + dC_{233} + dC_{241} + dC_{242} =$

1500 + 300 + 800 + 2000 + 120 + 700 +900 + 80 +200 +150 = 6600

Direct and open 2D (RP method):

$\sum dC_{nmp} = dC_{311} + dC_{312} + dC_{321} + dC_{322} + dC_{331} + dC_{332} + dC_{333} + dC_{411} + dC_{412} =$ 1500 + 300 + 700 + 1000 + 700 + 900 + 80 + 200 + 150 = 5530

5.1.2 Total Time calculation procedure

In the all-manufacturing process, time is one of the important indicator in the industrial. More competition between manufacture nowadays depending on the reducing time. According to GT, Total Time calculation was calculated by equation 3. In the equation 3 code, generation method was used like TC method. The index n show the manufacturing method and index m show procedure sequence.

$$\sum T = \sum dT_{nm} \text{ or } \sum IT_{nm} \tag{5.3}$$

$$\sum T = \sum T_{nm}$$

n: manufacturing method (1: conventional method, 2: machining method, 3: RP method)

m: procedure sequence (1: design, 2: pattern manufacturing, etc. variable in each method) for TT calculation same example was used at this part first one Direct and close 3D impeller manufacturing with RP method.

$$\sum T = \sum dT_{nm} = \sum dT_{31} + dT_{32} + dT_{33} + dT_{34} = 75 + 35 + 35 + 10 = 155$$

The second example Indirect and close 3D impeller manufacturing with RP method.

$\sum T = \sum IT_{nm} = IT_{31} + IT_{32} + IT_{33} + IT_{34} + IT_{35} + IT_{36} = 10 + 5 + 3 + 22 + 35 + 10 = 85$

Fig 41 shown TC comparison between Direct and Indirect (Reverse) 3D close Impeller manufacturing. It show that TC of Machining method is more than other methods.

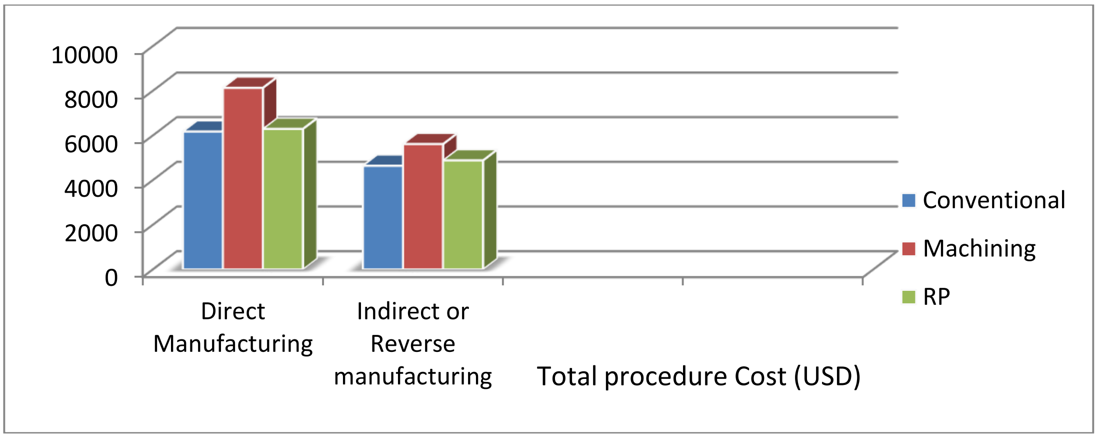


Figure 49: Total Cost comparison between Direct and Indirect (Reverse) 3D close Impeller manufacturing

Diagram analyses demonstrate that total procedure cost in reverse method is much less compare to direct impeller manufacturing procedure. It is obtainable in all the conventional, machining and RP methods. As it mentioned before it is because of design cost eliminating in reverse engineering method. Another fact about the diagram shows the less difference between conventional and RP procedure in cost point of view, but the dimensional accuracy of final manufactured impeller with RP technology is not comparable with conventional method and it is much accurate than conventional method. The dimensional accuracy or in other point of view, degree of compliance in both reverse impeller manufacturing and the conventional and RP method will be analyzed with COSMOS software and also hydraulic test. The results in both software analysis and hydraulic test analysis demonstrate more degree of compliance in RP method compare to conventional method, and it would be the adductive reason to implement RP technology in reverse engineering more than other methods. Degree of compliance in machining method is also much higher than conventional method but the total consumed cost of this procedure is not economical.

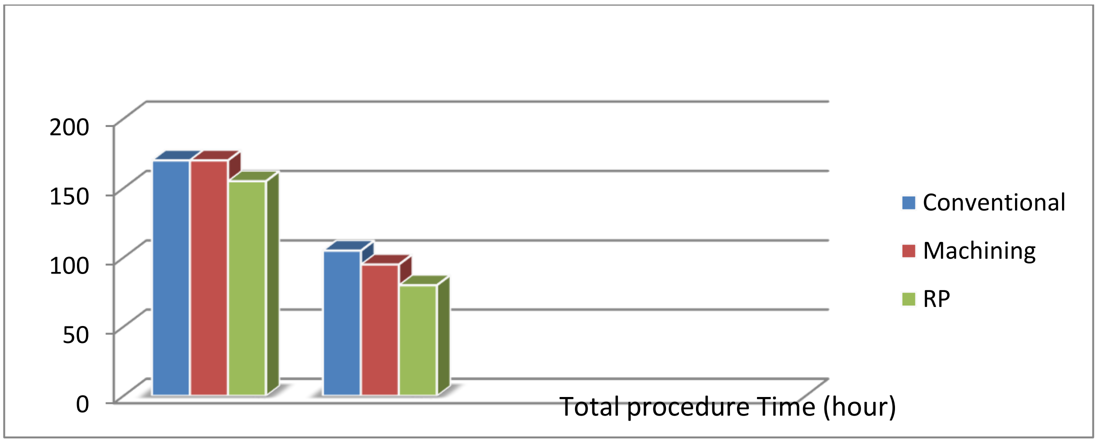


Figure 50: Total Time comparison between Direct and Indirect (Reverse) 3D close Impeller manufacturing with considering to different manufacturing procedure

Another fact about the methods is allocated time among the different procedures. The total allocated time diagram presents less procedure time in all reverse manufactured impeller, with different methods compare to direct manufacturing way. Also with considering in Cost diagrams which presents approximately similar cost between the conventional and RP methods, the difference is obtainable in allocated time diagram. Figure 42 show TT comparison between Direct and Indirect 3D close Impeller manufacturing. The specified cost in both methods is so close to each other but the consumed in RP method is less than both other method. Not only in reverse engineering but also in direct manufacturing.

Total cost of 3D pattern and core box manufacturing via implementing machining method is much higher than other methods and it is applicable just in cases which has logical vindicate such as aiming high surface quality and dimensional accuracy.

Total cost and Time of all the procedure and different types of impeller are also collected in one table. Comparison of impeller manufacturing methods was shown in table 4.

Table 4: Comparison of impeller manufacturing methods with consideration on Costs and lead Time.

				Cost (USD)	Time (Hour)
Direct Impeller manufacturing	Open	2D	Manually Core box manufacturing and normal casting	3095	140
			Impeller machining consist of conceptual design and CAD/CAM	6600	130
			Impeller manufacturing consist of conceptual design (CAD)- RP and normal casting	5530	130
		3D	Manually Core box manufacturing and normal casting	3445	150
			Impeller machining consist of conceptual design and CAD/CAM	9800	140
			Impeller manufacturing consist of conceptual design (CAD)- RP and normal casting	5680	135
	Close	2D	Manually Core box manufacturing and normal casting	5790	160
			Core box machining consist of conceptual design and CAD/CAM + Casting	7930	160
			Core box manufacturing consist of conceptual design (CAD)- RP and normal casting	6190	145
		3D	Manually Core box manufacturing and normal casting	6140	170
			Core box machining consist of conceptual design and CAD/CAM + Casting	8130	170
			Core box manufacturing consist of conceptual design (CAD)- RP and normal casting	6290	155
Indirect Impeller manufacturing (Reverse Engineering)	Open	2D	Impeller cut or impeller use manually to making core box and normal casting	2810	65
			Impeller cut- 3D scan- CAD/CAM)-Normal casting	4630	60
			Impeller cut- 3D scan- CAD (data analyzing)- RP-Normal casting	4350	73
		3D	Impeller cut or impeller use manually to making core box and normal casting	2945	70
			Impeller cut- 3D scan- CAD/CAM)-Normal casting	4885	67
			Impeller cut- 3D scan- CAD (data analyzing)- RP-Normal casting	4385	75
	Close	2D	Impeller cut or impeller use manually to making core box and normal casting	3240	80
			Impeller cut- 3D scan- CAD/CAM)-Normal casting	5170	90
			Impeller cut- 3D scan- CAD (data analyzing)- RP-Normal casting	4830	80
		3D	Impeller cut or impeller use manually to making core box and normal casting	4640	105
			Impeller cut- 3D scan- CAD/CAM)-Normal casting	5610	95
			Impeller cut- 3D scan- CAD (data analyzing)- RP-Normal casting	4880	80

5.2 Impeller Analyzing

Impeller analyzing at this study consist of hydraulic and computational analysis.

- Hydraulic test Analysis
- Computational Analysis (COSMOS software)

5.2.1 Hydraulic test Analysis

ISO 9906specifies hydraulic performance tests for customers' acceptance of rot dynamic pumps (centrifugal, mixed flow and axial pumps). It is intended to be used for pump acceptance testing at pump test facilities, such as manufacturers' pump test facilities or laboratories. ISO 9906 can be applied to pumps of any size and to any pumped liquids which behave as clean, cold water.

PUMPIRAN hydraulic tests laboratory guaranteed all the tests are performed concerned with ISO 9906 standard.

Terms and definitions

- **Guarantee point**

Flow/Head (*Q*/*H*) point, which a tested pump shall meet, within the tolerances of the agreed acceptance class.

- **Factory performance test**

Pump test performed to verify the initial performance of new pumps as well as checking for repeatability of production units, accuracy of impeller trim calculations, performance with special materials, etc.

- **Volume rate of flow**

Rate of flow at the outlet of the pump, given by: $Q = \frac{q}{\rho}$ q: Mass flow rate ρ: Density

(5.4)

- **Mean velocity**

Mean value of the axial speed of flow, given by:

$U = \frac{Q}{A}$ U: Mean Velocity (m / s) Q: (Volume) (m^3/s) A: (m^2)

(5.5)

- **Head**

Energy of mass of liquid, divided by acceleration due to gravity, *g*, given by:

$H = \frac{y}{g}$ H: Pump total head (m) y: Specific energy (J/kg) g: (m/s^2)

(5.6)

- **Velocity head**

Kinetic energy of the liquid in movement, divided by *g*, given by:

$U = \frac{U^2}{2g}$ U: Mean Velocity (m / s) g: (m/s^2)

(5.7)

- **Total head**

Overall energy in any section

Note 1 to entry: The total head is given by:

$$H_x = z_x + \frac{p_x}{\rho \times g} + \frac{U_x{}^2}{2 \times g} \quad (5.8)$$

H: Pump total head at any section (m) ρ: Density g: Acceleration due to gravity (m/s^2) U_x: Mean Velocity (m / s)

Where

z is the height of the center of the cross-section above the reference plane;

p is the gauge pressure related to the center of the cross-section.

Next tables and diagrams present the result of hydraulic test analysis data sheets. The data belong to specific pump of petroleum industry designed and manufactured by PUMPIRAN pump manufacturing industries. Technical specification of pump presented completely in tables. The impeller of mentioned pump is manufactured by two reverse engineering methods. First table and diagram are referring to impeller which is produced by implementing conventional method and casting procedure and the second one is refer to implementing RP method which is objective of this thesis. As a case study the diagrams present the degree of compliance among the final products also clarifies as acceptance factor of the selected procedure verifying as well.

Table 5: Test analysis data sheet of conventional manufactured impeller

PUMPIRAN	**TEST DATA ANALYSIS SHEET**	Date: Test : S No :	15.08.2014 L Ce-85170 EA 300-35

PUMP SPECIFICATION

Type: ETA 300-35	Speed (rpm): 1450	Imp. Diameter: 345	Power: 132.00

TEST CONDITION

Gravity (m/s²): 9.8	Density (Kg/m³) 1050	Suction Pipe (mm): 300.00
Discharge Pipe (mm): 200.00	Suction Gage Height: 0.0	Discharge Gage Height: 2.8

GUARANTY POINT(S)

Point(S)	Capacity (m³/h)	Head (m)	Power (Kw)	Efficiency (%)	NPSH (m)
1	0.00	37.60			
2	500.00	34.60			
3	800.00	32.00			
4	1300.00	26.00			
5	1800.00	17.00			

MEASURED VALUES

Test points	1	2	3	4	5	6	7	8	9	10
Speed (rpm)	1495	1495	1495	1490	1490	1490	1490			
Capacity (m³/h)	54.00	324.00	612.00	936.00	1170.00	1458.00	1638.00			
Suction Head (bar)	0.28	0.27	0.25	0.20	0.17	0.10	0.05			
Discharge head (bar)	4.18	3.90	3.55	3.00	2.60	1.85	1.40			

CALCULATED DATA

Suction $V^2/2g$	0.00	0.08	0.30	0.69	1.08	1.67	2.11			
Discharge $V^2/2g$	0.01	0.42	1.49	3.49	5.46	8.48	10.70			
Total Head (m)	42.59	40.16	37.66	34.16	31.97	27.45	25.16			

CORRECTED TEST DATA

Speed (rpm)	1450.0	1450.0	1450.0	1450.0	1450.0	1450.0	1450.0		
Capacity (m³/h)	0.00	314.25	593.58	910.87	1138.59	1418.86	1594.03		
Total Head (m)	40.06	36.50	32.12	25.91	20.93	14.87	12.78		

COMMENTS

Prepared by:		Approved by:		stamp	

Main parameters about performance of each pumps is related to Head (m) and Capacity (m³/h) curves. Table 5 show the test analysis data sheet of conventional manufactured impeller and figure 43 show the Pump performances Curve for Conventional manufacture impeller. These curves also applicable in pump selecting procedure. Normally X axis of diagram presents Capacity and Y axis is related to pump head. Head (H) and Capacity (Q) in both cases are compared with main impeller performance and the curves drawn with considering to these parameters.

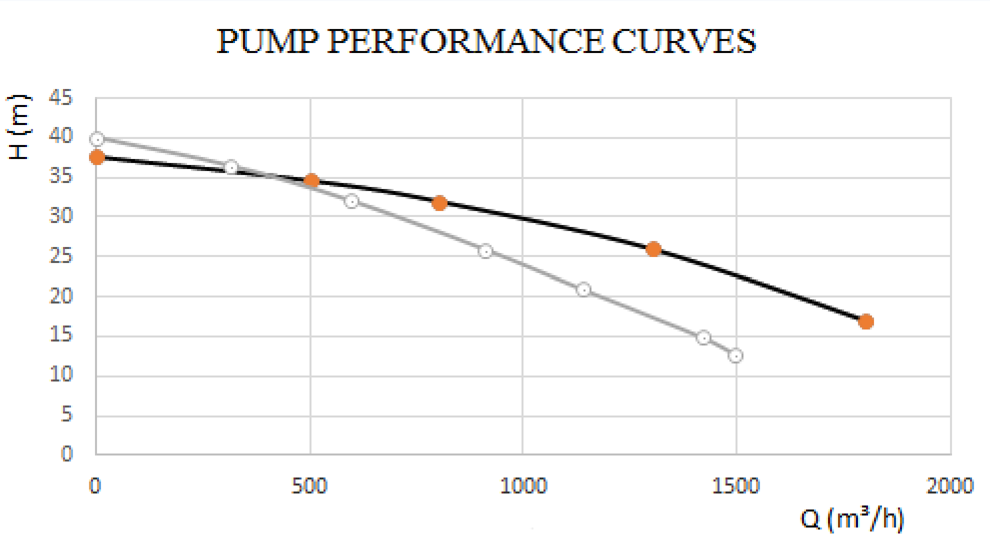


Figure 51: Pump performances Curve for Conventional manufacture impeller

Table 6: Standard and Tolerance table

TYPE	ETA 300 - 35	
TEST STANDARAD	Acceptance Tolerance acc. To ISO 9906	
	Tolerance	
	Q (m^3/h)	H (m)
	± 8 %	± 5 %

As it obtainable in diagram the curve related to traditional reverse engineered impeller is taken distance from main impeller curve and it presents that not satisfy the desired features. Especially as it recognizable from diagram in capacities more than 500 m^3/h it has dramatic reduction in head. The difference is near 10 m and that's not acceptable by manufacturer. Test analysis data sheet of RP manufactured impeller is shown in table 7.

Table 7: Test analysis data sheet of RP manufactured impeller

PUMPIRAN	**TEST DATA ANALYSIS SHEET**	Date: Test : S No :	15.08.2014 L Ce-86105 G 047

PUMP SPECIFICATION			
Type: ETA 300-35	Speed (rpm): 1450	Imp. Diameter: 345	Power: 132.00

TEST CONDITION		
Gravity (m/s²): 9.8	Density (Kg/m³) 1050	Suction Pipe (mm): 400.00
Discharge Pipe (mm): 200.00	Suction Gage Height: 0.0	Discharge Gage Height: 1.0

GUARANTY POINT(S)

Point(S)	Capacity (m³/h)	Head (m)	Power (Kw)	Efficiency (%)	NPSH (m)
1	0.00	37.60			
2	500.00	34.60			
3	800.00	32.00			
4	1300.00	26.00			
5	1800.00	17.00			

MEASURED VALUES

Test points	1	2	3	4	5	6	7	8	9	10
Speed (rpm)	1495	1495	1495	1490	1490	1485	1485			
Capacity (m³/h)	0.00	324.00	612.00	936.00	1170.00	1458.00	1692.00			
Suction Head (bar)	0.26	0.26	0.25	0.21	0.19	0.18	0.14			
Discharge head (bar)	4.20	3.95	3.60	3.10	2.60	1.95	1.25			
Abs. Current (A)	202.60	207.00	212.50	231.00	237.00	254.00	263.00			
Voltage (V)	221.10	218.00	217.80	216.60	217.80	217.00	216.30			
Abs. Power (KW)	112.40	114.30	117.50	128.40	132.90	142.30	147.50			
CALCULATED DATA										
Suction V²/2g	0.00	0.03	0.09	0.22	0.34	0.53	0.71			
Discharge V²/2g	0.00	0.42	1.49	3.49	5.40	8.48	11.42			
Total Head (m)	41.19	39.03	36.57	33.57	30.70	27.00	23.03			
Hydraulic power (K)	0.00	34.46	60.98	36.09	97.88	107.23	106.17			
Total Efficiency (%)	0.00	0.30	0.52	0.67	0.74	0.75	0.72			
CORRECTED TEST DATA										
Speed (rpm)	1450.0	1450.0	1450.0	1450.0	1450.0	1450.0	1450.0			
Capacity (m³/h)	0.00	314.25	593.58	910.87	1138.59	1423.64	1625.12			
Total Head (m)	38.75	36.72	34.40	31.97	29.07	25.75	21.95			
Abs. Power (KW)										
Hydraulic power (K)										
Total Efficiency (%)										

COMMENT

Prepared by:		Approved by:		stamp	

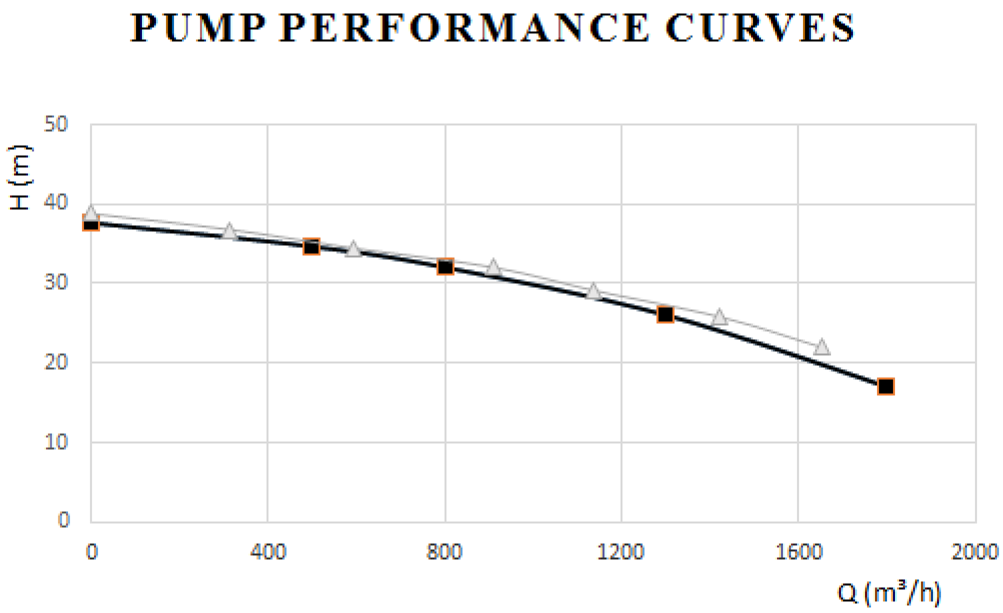


Figure 52: Pump performances Curve for RP manufacture impeller

Table 8: Standard and Tolerance table

TYPE	ETA 300 - 35	
TEST STANDARAD	Acceptance Tolerance acc. To ISO 9906	
	Tolerance	
	Q (m^3/h)	H (m)
	± 8 %	± 5 %

As it obtainable from diagram, the results are so coincident with the main impeller curves. As result it can be interpret that reverse manufactured impeller utilizing RP technology is satisfy the desired feature of pump and it is applicable as a case of impeller reverse engineering. Figure 44 Pump performances Curve for RP manufacture impeller.

5.22 Computational Analysis

The Solid Works software is used for modeling the impeller and analysis is done in COSMOS Workbench. The COSMOS software is Advanced Finite Element Package used for determining the variation of stresses, strains and deformation across profile of the impeller. An attempt has been made to investigate the effect of the pressure and induced stresses on the impeller. The Static Structural Analysis has been performed to investigate the Von-Miss stresses, strains and Deformations of the impeller.

5.2.21 Finite Element Analysis

Finite element analysis is a computer based numerical technique for calculating the strength and behavior of engineering structures. It can be used to calculate deflection, stress, vibration, buckling behavior and many other phenomena. It can analyze elastic deformation or “permanently bent out of shape” deformation. The computer is required because of the astronomical number of calculations needed to analyze a large structure. The power and low cost of modern computers has made finite element analysis available to many disciplines and Companies.

Meshing:

The geometry and the mesh of a 3D close pump impeller domain is generated using COSMOS Workbench. An unstructured mesh with tetrahedral cells is also used for the zones of impeller as shown in the figure. The mesh is refined as in the regions close to the leading and trailing edge of the blades. Around the blades, structured hexahedral cells are generated to obtain better boundary layer detail. A total of 12022 are generated for the impeller domain. Mesh statics are presented in table 11.

Boundary Conditions:

Pump impeller domain is considered as rotating frame of reference with a rotational speed of 1450 rpm. The working fluid through the pump is petroleum at 16ºC. Turbulence model with turbulence intensity of 5% is considered. Inlet static pressure 1kg/cm2 and outlet mass flow rate of 0. 5m 3/s are given as boundary conditions.

VON MISES STRESS:

The Von Mises criterion is a formula for calculating whether the stress combination at a given point will cause failure. Formula is for combining X, Y and Z direction stresses into an equivalent stress, which is then compared to the yield stress of the material. The equivalent Stress is often called the “Von Mises Stress" as a short hand description. It is not really a stress, but a number that is used as an index. If the "Von Mises Stress" exceeds the yield stress, then the material is considered to be at the failure condition.

Von mises stress formula $(S1-S2)^2 + (S2-S3)^2 + (S3-S1)^2 = 2Se^2$ Where S1, S2 and

S3 are the principal stress and Se is the equivalent stress (or) “Von mises stress”.

Table 11 & 12 show the information about Mesh for impeller.

Table 11: Mesh Information table for Impeller

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	8.76813 mm

Tolerance	0.438406 mm
Mesh Quality	High

Table 12: Mesh Information – Details

Total Nodes	23244
Total Elements	12022
Maximum Aspect Ratio	41.178
% of elements with Aspect Ratio < 3	58.6
% of elements with Aspect Ratio > 10	4.8
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:15
Computer name:	BEHZAD-PC

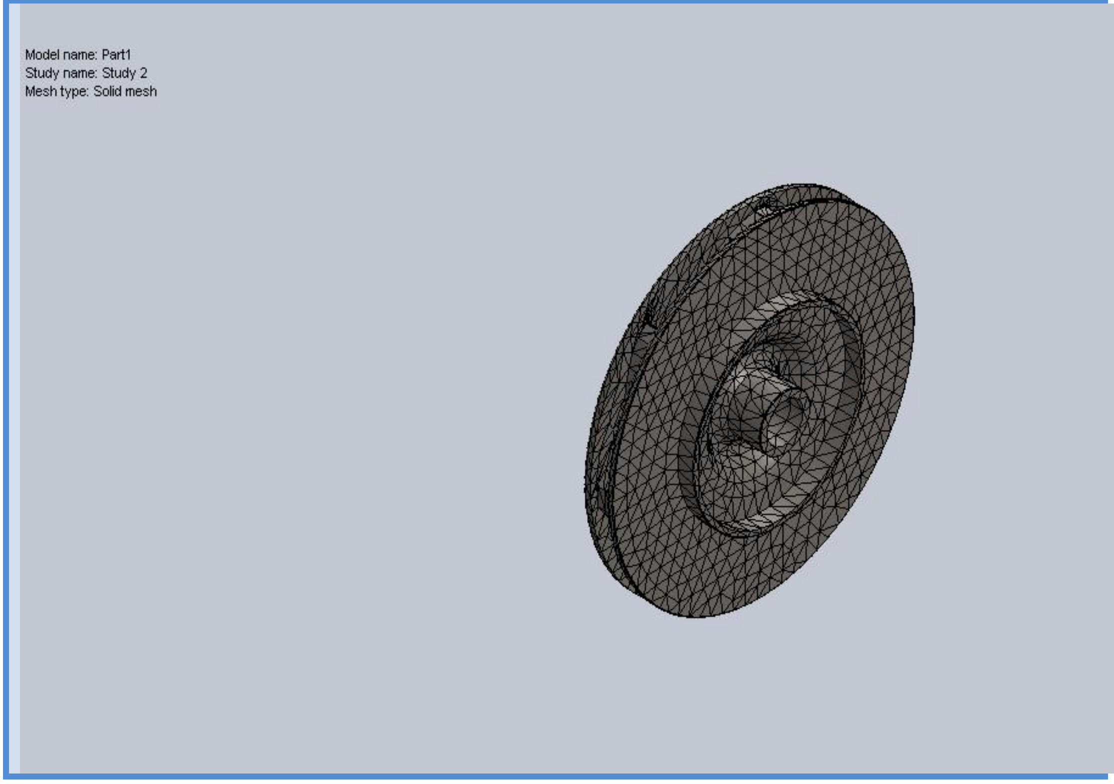
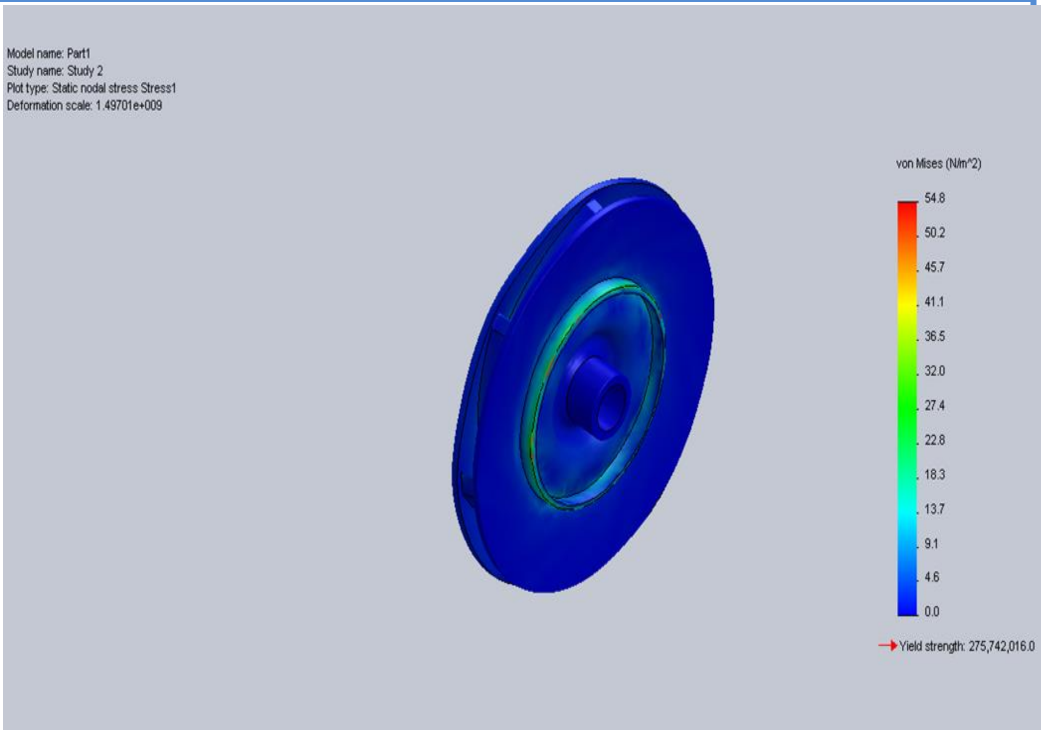


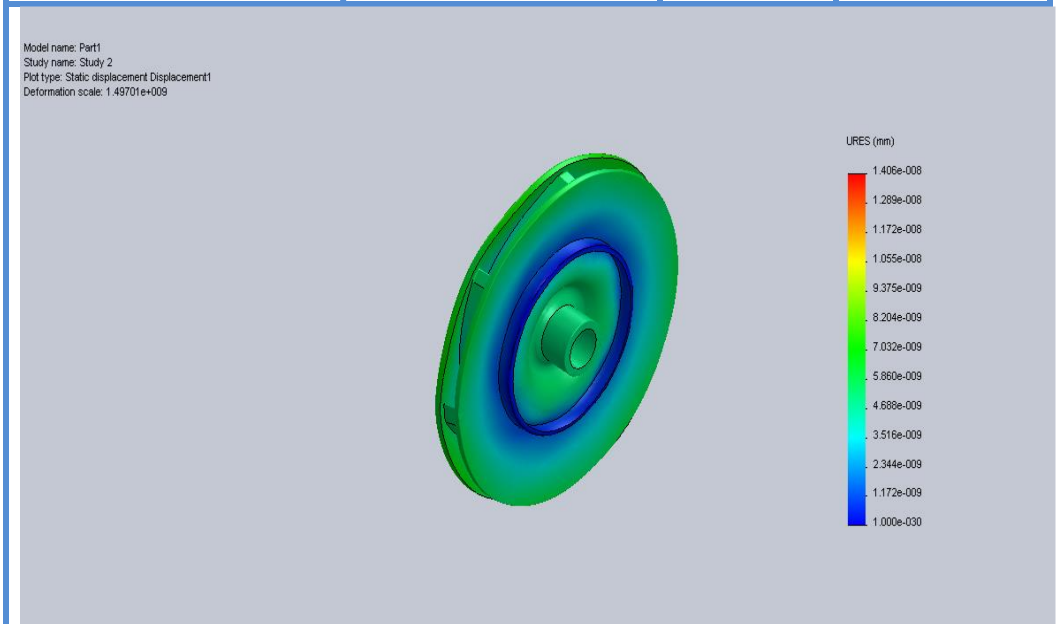
Table 13: Study Results1

Name	Type	Min	Max
Stress1	VON: Von Mises Stress	0.0165719 N/m^2 Node: 17406	54.7823 N/m^2 Node: 17614



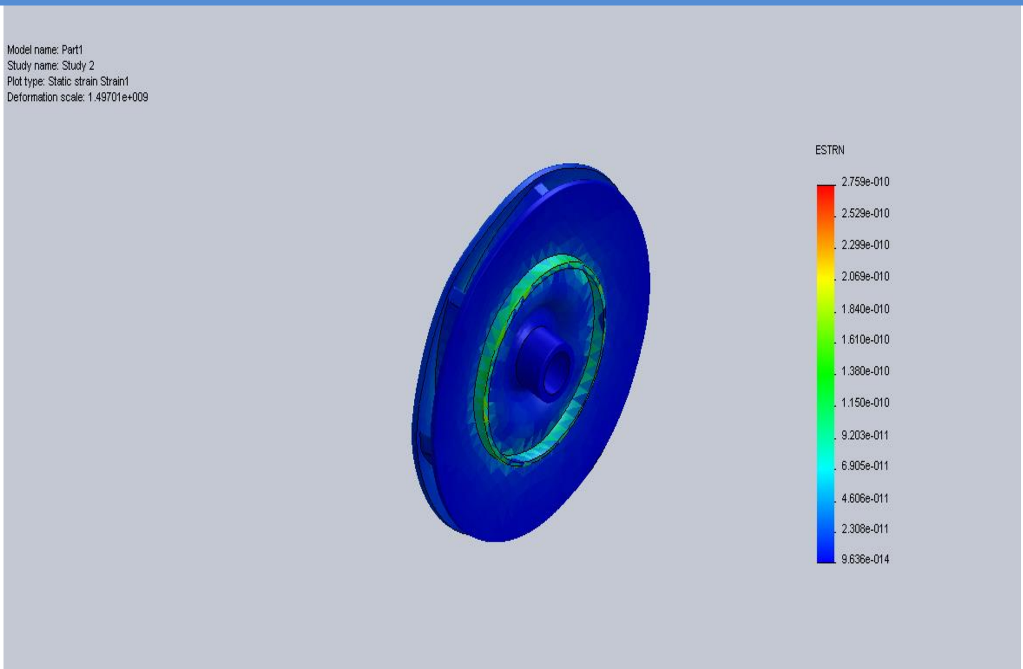
Part1-Study 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 mm Node: 763	1.40632e-008 mm Node: 12725



Part1-Study 2-Displacement-Displacement1

Table 14: Study result 2

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	9.63586e-014 Element: 4317	2.75894e-010 Element: 7747
 **Part1-Study 2-Strain-Strain1**			

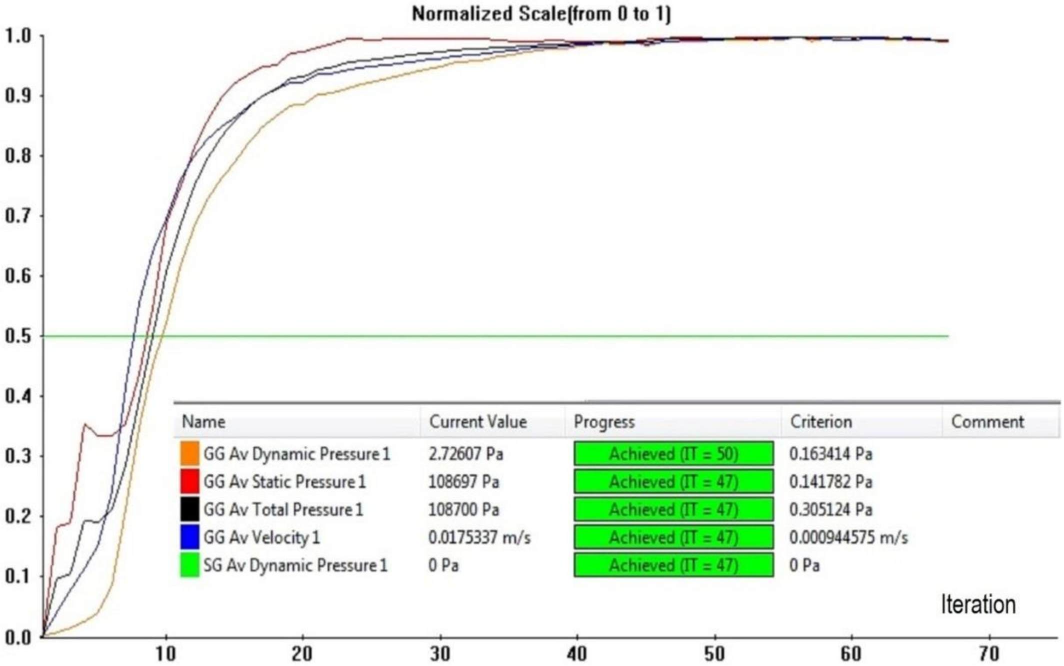


Figure 53: Normalization diagram

Iteration cycle:

With considering to ISO 9906 standard, in pump impeller manufacturing, the acceptance rate which starts in periodic cycle of 45_ 60 has to be reach in 100% normalization and be constant till to periodic 70 irritations figure 54. The implanted analysis with COSMOS software illustrate that manufactured impeller is satisfying the standards.

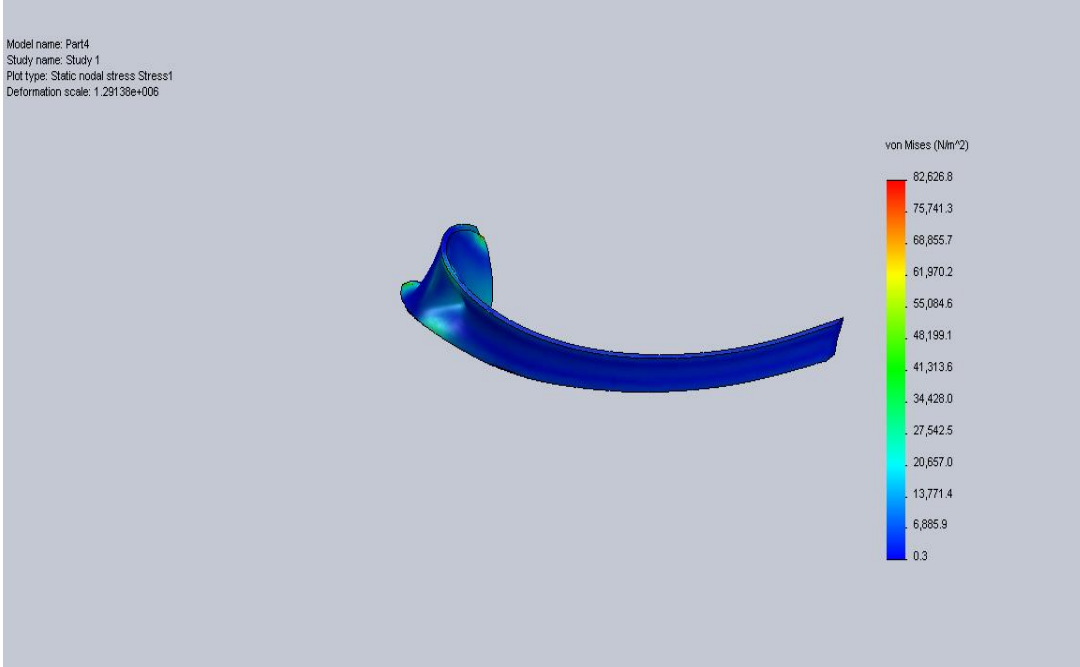
Same analysis have been done for separate just for one blade. Table 15 show the information about mesh for blade. Table 16 illustrated the result of this analysis.

Table 14: Mesh Information table for Blade

Total Nodes	15724
Total Elements	8224
Maximum Aspect Ratio	17.937
% of elements with Aspect Ratio < 3	98.5
% of elements with Aspect Ratio > 10	0.0973
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:05
Computer name:	BEHZAD-PC

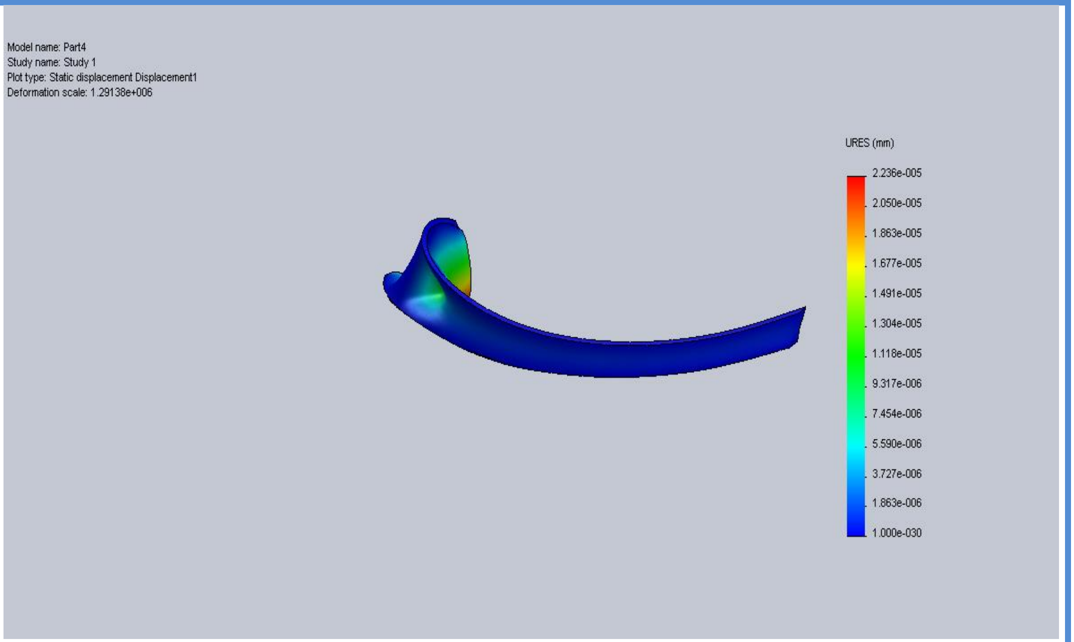
Table 15: Study result 3

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.346603 N/m^2 Node: 6627	82626.8 N/m^2 Node: 1824



Part4-Study 1-Stress-Stress1

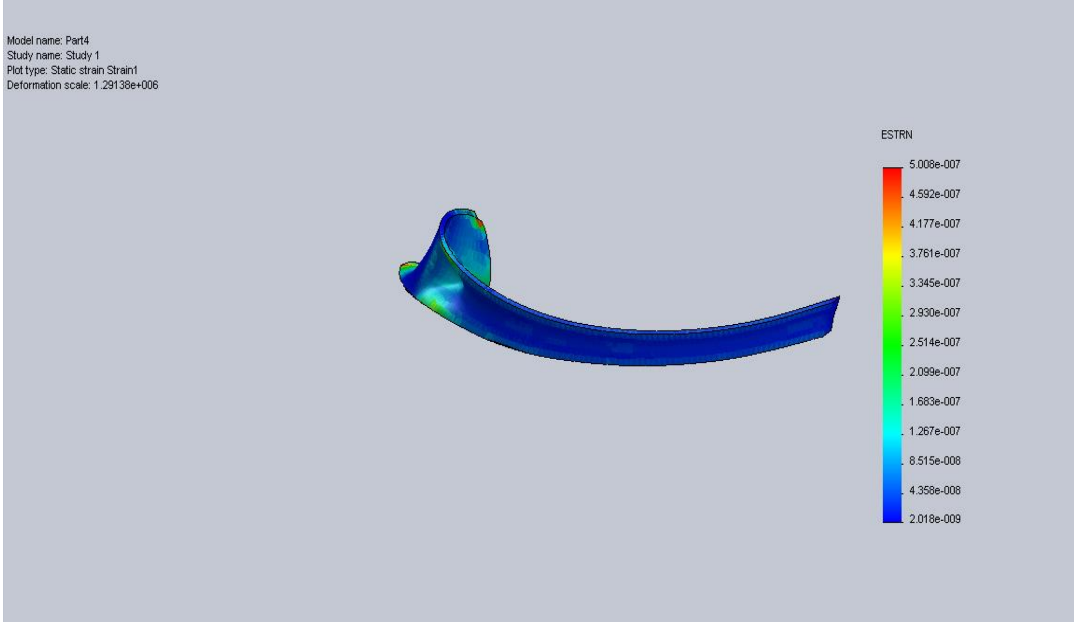
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 mm Node: 1	2.23606e-005 mm Node: 5654



Part4-Study 1-Displacement-Displacement1

Name	Type	Min	Max

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	2.01815e-009 Element: 4825	5.00815e-007 Element: 1761



Part4-Study 1-Strain-Strain1

Chapter 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This thesis study utilizing Rapid prototyping technology in reverse engineering of specific pump impeller. The investigated impeller is 3D shape blade and close type which is the most challengeable type of impeller manufacturing in pump industry. 3D blade shapes impeller reverse engineering utilizing Rapid Prototyping method combined with casting procedure is obtained to present robust performance while compared to other existing methods. Investigated parameters consist of time intransitive and cost separately in each type of impeller manufacturing presented in Table 4.

The approached results are classified as follow:

- Utilizing RP technology caused to enormous time reduction in initial pattern manufacturing procedure compare to both traditional and machining way.
- Total cost of 3D pattern and core box manufacturing via implementing machining method is much higher than other methods and it is applicable just in cases which has logical vindicate such as aiming high surface quality and dimensional accuracy.
- Surface quality and dimensional accuracy in both machining and RP method is much better than conventional manufacturing methods.

- The results of surface quality and dimensional accuracy considerably are obtainable from impeller hydraulic test analysis.
- Investigable parameters about pump performance are Head (m) and capacity (m^3/h) , presented by H and Q curves respectively, shows demonstrative coincident between the original impeller curve and reverse manufactured pump utilized RP method.
- Conventional pattern and core box manufacturing take less costs compare to other methods. Since the operation is done manually, so the dimensional accuracy wouldn't be so dependable. Diagram related to this procedure present dramatic difference between desired parameter and standard condition.
- Pump performance data analyzing in regard of cost and time intransitive issues, presents the RP method utilizing is dependable and applicable method in reverse engineering case of complicated blade shapes.

6.2 Recommendation

Complicated shape manufacturing or reverse engineering are the challengeable concepts for manufacturer. In this regard 3D shape impeller consist of pump impeller and also turbine or jet impellers manufacturing which are classified as high precision manufacturing involved with novel methodology application to increase the performance and optimize the manufacturing parameters. Rapid prototyping and rapid tooling are the methodologies which are applicable in this regard due to high degree of compliance and satisfying the desired characteristics.

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