Reverse Engineering, CAD\CAM & pattern less process applications in casting-A case study

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Abstract—This paper details about pattern less casting process using CAD\CAM applications, scanning/digitizing, coordinate measuring arm machine, and 5-axis machine. One of the advantages is that the casting lead time is reduced drastically as compared to conventional methods of casting with patterns. An adjustable diffuser vane blade used in oil and gas industry was manufactured by reverse engineering and pattern less process starting from a worn out sample. First the blade was digitized by Cimcore-3000i 3D Coordinate Measuring Arm. The obtained point cloud data is imported to Pro/Engineer CAD\CAM software to develop the 3D model and design the moulds. Then direct sand blocks (cope and drag) milling on Poseidon CNC specific purpose 5-axis machine was adopted completely eliminating any use of patterns. The moulds were directly used for metal pouring at the casting stage.

Keywords- pattern less process, reverse engineering, vane blade, 3D Coordinate Measuring Arm, CNC machining,digitizing

I. Introduction

In ancient times (circa 1000 AD), it would take 3-4 months to make a bronze casting idol through investment casting, starting from the carving of a wax statue, covering with clay, drying in the sun, dewaxing, metal pouring, demoulding, and finally finishing the casting [1]. In the last century, which witnessed manufacture of castings on a large scale, the lead-time for developing a typical casting was however, not very different: about 8-12 weeks. This was mainly due to several weeks (over 70% of total lead-time) consumed by tooling development and production trials. Such lead-times are no longer acceptable. With rapidly compressing product development times (typically 12-15 months for a new automobile), OEMs now expect a new casting to be developed in days, not weeks and months. This is however, easier said than done, since the demand for shorter lead-time is also accompanied by the need for quality assurance and cost reduction. All these cannot be simultaneously achieved unless new technologies (like CAD and simulation) and methodologies (like design for manufacture and collaborative engineering) are employed for casting development

In general, development of a new casting broadly comprises three distinct phases: product design (in OEM firm), tooling development (in a tool room), and casting production (in a foundry). Most OEM firms now make use of CAD programs for solid modeling and shape optimization. Creating a 3D model of the part is a time-taking task, but essential for computer-aided casting development. For existing parts, the solid modeling time can be minimized by reverse engineering: scanning the part geometry using a contact or non-contact (laser) scanner. The tool rooms can use software programs for tool design (pattern and core box), including application of various allowances like draft, shrinkage and machining. The foundry engineer can use software programs for (1) methoding or rigging (design of feeders and gating system), and (2) casting simulation (mould filling and solidification) to predict casting defects, and to optimize the methoding for achieving the desired quality and yield. The fabrication is tooling is facilitated by CAM programs for tool path generation and CNC manufacture of tooling. This lead-time can be further compressed by using rapid prototyping based tooling, referred to as rapid tooling.

Feedback from tooling development and casting trial (real or virtual) is useful and indeed necessary to improve the design of product and tooling considering manufacturability (Fig.1). For example, undercut features that necessitate an additional core or non-planar parting can be eliminated to reduce the tooling costs. Similarly, thin intermediate features that cool early and hinder mould filling or solidification feeding can be increased in size to prevent cold shut and shrinkage porosity defects, respectively. This can be facilitated through collaborative engineering between foundry, tooling and OEM engineers, resulting in early prediction and prevention of potential production problems (better quality assurance), and saving valuable time and costs [2].

Pattern is a replica of the object to be cast, used to prepare the cavity into which molten material will be poured during the casting process. Patterns used in sand casting may be made of wood, metal, plastics or other materials. Patterns are made to exacting standards of construction, so that they can last for a reasonable length of time, according to the quality grade of the pattern being built, and so that they will repeat ably provide a dimensionally acceptable casting [3].

Problems in today's foundries

- Shorter time to market and more flexibility
- Shorter lead time from design to production
- Smaller batch sizes
- Prototype production and more complicated design
- Prototype production cost too high with traditional process
- Logistic and storage costs increasing, specially with big Patterns

However with the advances in computing capabilities and Solid Freeform Fabrication technology (SFF) have made the designer's or patternmaker's 'science fiction' fantasy a reality for many part designers. All the designer needs to do is complete a three-dimensional (3-D) computer-aided design (CAD) model of the required shape and he has to click on a print icon[4] .

SFF technologies use computer graphic representation and simple stock material to fabricate complex parts. Fused Deposition Modeling (FDM) 2, Laminated-Object Manufacturing (LOM) 3, Selective Laser Sintering (SLS)4 and 3D printing5 can create functional parts in production materials ranging from plastic and nylon to ceramic and powdered metals. And with advanced computer numerical controlled (CNC) machining, metal parts with complex external shapes can be easily produced in limited quantities.

But, for designers of metal parts with complex internal geometries like cylinder heads, manifolds or transmission housings, traditional foundry sand casting is still the method of choice for producing production-intent prototype parts for functional testing. This new desktop manufacturing paradigm remains a dream. To create their functional cylinder head, the designer will need to design a set of tools or patterns for conventional sand casting. Of course, the design of each of these components must consider appropriate shrinkage factors for the particular alloy she has in mind. Even for an experienced mould designer, it will take several iterations to get a solid casting that is free from any porosity.

Every time a design changes, these tools must be modified or scrapped. By employing pattern less casting, designers can better optimize their designs and eliminate hundreds of thousands of dollars wasted in retooling costs.

One technique for pattern less casting, called Sand Form, was pioneered by DTM Corporation. In this process, foundry sand mixed with an organic binder is formed into a mould using an SLS machine. The sand is deposited in a thin layer and the shape of the part is sintered with a laser beam. The mould, complete with integral cores, is built up one layer at a time. Molten metal is then poured directly into the mould. Once the metal is cooled, the mould is broken away revealing the near net shape part.

Another technique for creating moulds directly from a 3D CAD design is called Direct Shell Production Casting (DSPC) and was developed by Solingen Technologies, Inc. DSPC uses 3-D printing to create a ceramic mould with integral cores. A thin layer of ceramic powder is spread and then an ink jet print head deposits a silicate binder onto the powder in the shape of the part. After the shell is built, complete with gates and riser , the loose powder is removed and molten metal poured into the remaining shells[4].

The other method developed by Castings Technology International (CTI),UK involves direct machining of sand moulds and cores from blocks of sand on a special purpose CNC machine with machining accuracy of 0.01mm using specially developed cutters with minimal wear. The Pattern less® Process was invented and developed by CTI. It is a technique whereby moulds are directly machined out of blocks of sand. This proves to be a very cost effective way of producing one-off or small production run castings, since it does not require the manufacture of patterns and core boxes [5].

The benefits associated with this process include:

- Reduced time to manufacture
- Reduce total manufacturing costs
- Appropriate surface finish and enhanced letter definition
- Suitable for castings of all sizes and weights
- Opportunities for one off and small series production
- No pattern storage or maintenance costs [5]

Pattern less casting, using either of these techniques, offers a variety of benefits to the designer. Early design concepts can be tested and compared with no regard to the undercuts, parting lines and core prints usually required in sand casting. Since no cost-prohibitive tools are created, multiple part configurations can be produced and tested simultaneously. Design modifications are easily accommodated in CAD and require no retooling. The time between iterations can be reduced by 50%, allowing for better design optimization and reduced time to market [4].

The Reverse Engineering (RE) technique is one of the working tools in the Integrated Engineering that permits the optimization of the products' design and performance, so that the aim for a flexible production with minimum costs, high quality and offered to its beneficiaries as soon as possible, become more and more a tangible reality. This technique of recent date in terms of modern production systems, still has a relatively limited application, it being accessible particularly to specialists from important universities and industrial units, who possess already structured knowledge and procedures and what is more important, who can afford modern, but still expensive, equipments and facilities.

To many specialists, mainly those from small and medium enterprises or universities, the Reverse Engineering technique still seems an exotic alternative, although the advantages of its use are evident. Although the use of the Reverse Engineering technique as working tool is more and more spread in USA and Europe, in Saudi Arabia it seems to be still in the exploration phase.

In the absence of some sufficiently cogent information in the industrial field, existing data shows that in institutes of research and universities, although approached with interest, this technique stands at the beginning. In Saudi Arabia, at present, the scientific publications do not give evidence of woks on this issue.

One of the limitations of the development of this study is also the concern that many of the fully developed Reverse Engineering techniques require expensive equipments (three-dimensional measuring and scanning machines, rapid prototyping machines, computers with considerable hardware and software resources.).[6].

Reverse Engineering has been defined as a process for obtaining the technical data of a critical spare component. Computer-aided reverse engineering relies on the use of computer-aided tools for obtaining the part geometry, identifying its material, improving the design, tooling fabrication, manufacturing planning and physical realization. A solid model of the part is the backbone for computer-aided reverse engineering. The model data can be exported from or imported into CAD/CAE/CAM systems using standard formats such as IGES, STL, VDA and STEP.[7]

Reverse engineering can greatly reduce the time taken to create the solid model of a part, if a physical replica already exists. The part geometry is digitized using a contact or non contact system. The resulting point cloud is stitched together using specialized software to create the part model[8]..Each method has its own advantages and disadvantages which are discussed below:

Advantages of contact type digitizing process includes (i) high accuracy,(ii)ability to digitize/measure deep holes/slots and features,(iii)insensitive to reflecting/transparent surfaces,(iv)less cost. The disadvantages are slower process and distortion of softer objects by the probe.

Similarly the advantages of non-contact type digitizing process are faster process, no physical contact, insensitive to softer materials, good accuracy, and ability to scan intricate areas where touch probes diameter may be too large to accomplish the task. The disadvantages being sensitive to reflective/transparent surfaces, low accuracy, uncontrollable point data, high cost of equipment.

Solid modeling is a technique for representing solid objects suitable for computer processing. Other modeling methods include surface models and wire frame models. [8] Primary uses of solid modeling are for CAD, engineering analysis, [9] computer graphics and animation, rapid prototyping, medical testing, product visualization and visualization of scientific research.

While computer-aided manufacturing (CAM) is the use of computer-based software tools that assist engineers and machinists in manufacturing or prototyping product components. Its primary purpose is to create a faster production process and components with more precise dimensions and material consistency, which in some cases, uses only the required amount of raw material (thus minimizing waste), while simultaneously reducing energy consumption.

CAM is a programming tool that makes it possible to manufacture physical models using computer-aided design (CAD) programs. CAM creates real life versions of components designed within a software package. CAM was first used in 1971 for car body design and tooling. Integration of CAD and CAM environment requires an effective CAD data exchange. Usually it had been necessary to force the CAD operator to export the data in one of the common data formats, such as IGES or STL, that are supported by a wide variety of software. The output from the CAM software is usually a simple text file of G-code, sometimes many thousands of commands long, that is then transferred to a machine tool using a direct numerical control (DNC) program. [10][11].

This paper describes how the 3D CAD model developed from reverse engineering data was used to design moulds and subsequently how the moulds were directly machined out of sand blocks on a CNC machine totally eliminating patterns.

The above technologies are briefly described in this paper, highlighting our efforts toward indigenous development and application, focusing on bottleneck and least-explored areas with the largest potential for lead-time reduction. The first major work involved data capturing by reverse engineering method.. The second is benchmarking some of the most widely used pattern less processes. The third one being casting without any pattern These three works are briefly described in the following sections

The methodology proposed in this paper is presented in (*figure.1*.)

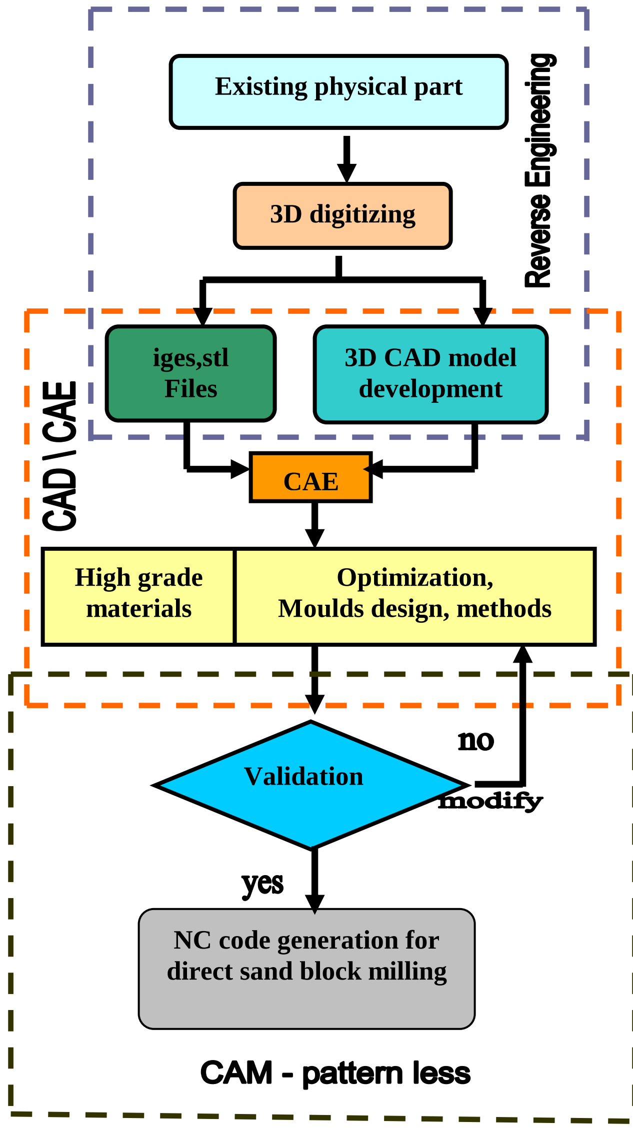

Figure.1
Proposed methodology integrated with CAD\CAM

II. PROBLEM DEFINITION

The case study presents the replacement of vane blades in the diffuser, which were worn out due to erosion (*Figure.2*), with

the new ones performed by using latest techniques of reverse engineering and patter less casting.
As there are is no supply from the vendor and due to non availability of drawings in any form, reverse engineering methodology was adopted.
As it very tedious even for an expert pattern maker to make a template of blade profile to be used during patterns making process ,an attempt has been made to direct machining of the sand blocks by design cavity moulds in the CAD software.

Figure.2
Worn out blades in the hub assembly

II. PROBLEM SOLUTION

A. Data capturing/digitizing process

In this work, the methodology of digitization and collection of coordinates of every point of contact of probe with the part surface has been adopted to have better control over the points while CAD model development. Though this process is very slow to collect enormous points for cloud of points, it is most useful for inspection purpose. It has high accuracy compared to all other mechanical methods.

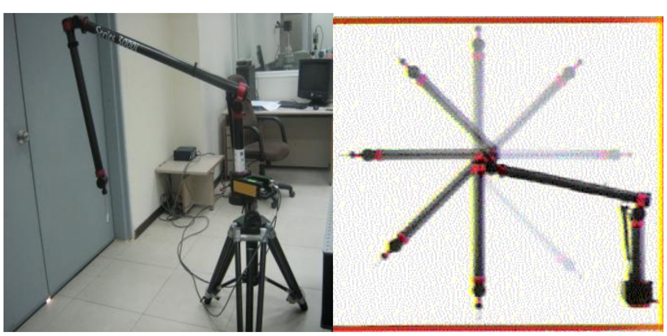

Figure.2
.Cimcore-3D coordinate measuring arm with RE Facility used for data capturing

Before scanning/digitizing, certain parameters have to be set so as to achieve the required accuracy in captured data, the important ones being , pitch, step over , area to be scanned tc.It is also necessary to do the Z-plane setting, axis alignment and X-Y-Z references.
Once the references and planes are determined, the Following steps are followed

1. Define area patches by marking boundary edges as shown in Figure.3
2. Processing cloud points. This includes merging of points cloud if the part is scanned in several settings.
3. Manually probe the edge boundaries.
4. Create reference surface.
5. Digitize the reference surface.
6. Reduce the gaps on edge boundaries and stitching the patches.

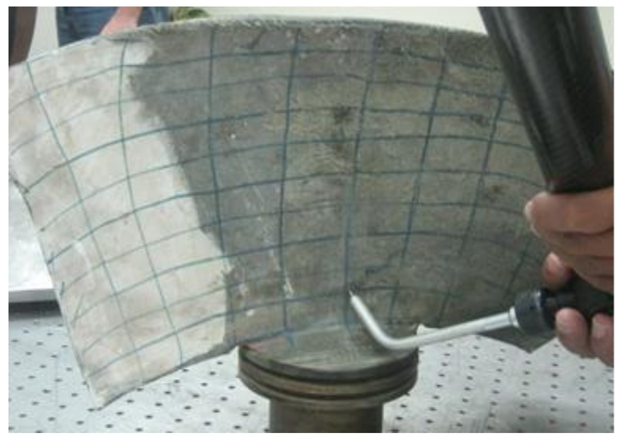

Figure.3
Digitizing the blade surface with point probe

The sequential steps of the CMM data are to first convert the points in to Lines, Arcs, Curves, and Surfaces. After manipulating, the data collected is converted into surface model or a solid model. This solid model is used for downstream operations such as mold design, CNC program generation etc.

B. Computer Aided Design (CAD) stage

The captured point cloud data is converted into polylines and the file was translated to IGES file format and imported to Pro/E software. The data available in the IGES is polyline segments. The segments are converted in to datum curves by using various datum curve editing/creating option within the software. It is a tedious process and the accuracy depends on the skill and expertise of the CAD engineer. All the datum curves are converted into surfaces, manipulating/stictching the patches by trimming and extending surface. Finally the model is converted into solid model, the cross section of which is showed in *(Figure.4)*

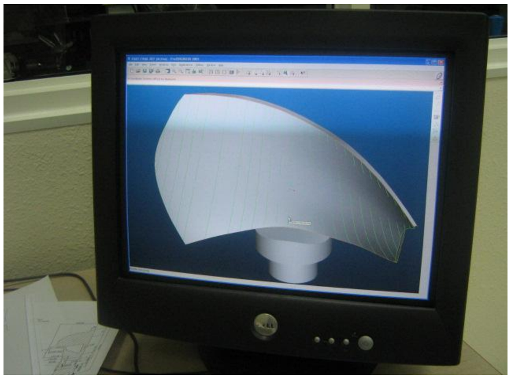

Figure.4
Surface model development from digitized data

Probe calibration time	06 min
Digitizing process on both sides	1hr 20min
Editing the points cloud data	30min
Creating /editing of curve mesh on either sides	2.5 hrs
Surface/solid model creation	2 hrs

Table.1. Average duration of digitizing process on both the sides of blade surface and 3D model development

C. Mould design for pattern less casting

Pattern less molding is a process where the steps of creating an actual pattern of wood, steel, urethane, etc. are bypassed and the desired shape is machined directly into the sand mold. It is very flexible because the shape is stored as an electronic image and converted to a machining language for actual production.

Design changes can be made quickly and efficiently within the electronic world with a high level of confidence that all resulting dimensions will be accurate. Changes can be made at anytime up until the mold cavity is cut. Time to market for any size program, but especially low volume and prototype is cut in half.

The most important decision in pattern and mould design is about the parting line. It affects and is affected by part orientation, design of pattern and cores, number of cavities in the mould, location of feeders, and channels for gating, cooling and venting. In this chapter, we will first develop a scientific definition of parting line, followed by the design of parting line, pattern, mould cavities and cores.

The parting or separation between two or more segments of a mould is necessary to create the mould cavity (as in sand casting) and also to remove the manufactured part from the mould (as in die casting). For any given casting geometry, a number of parting alternatives may exist; visualizing and selecting the best alternative is a non-trivial task even for simple shapes. Variations in customer requirements, quality specifications, manufacturing facilities and economical considerations may lead to different parting solutions for the same shape. For intricate parts, there is a high possibility of overlooking feasible alternatives and difficulty in assuring that the selected alternative is the indeed the best one.

Parting surfaces may be classified based on the type of mould segments at the interface. Considering three types of mould segments: cope, drag and cores, we have cope-drag, cope-core, drag-core and core-core parting surface. In practice, only cope-drag interface is referred to as the parting surface. The logic can be extended to die casting, by replacing cope and drag with the moving and fixed die half. The cope-core and drag-core interfaces correspond to the portions of mould that are contact with a core. The core-core interface is encountered in core assemblies (or dies with multiple inserts in contact with each other). The interfaces between the segments of a three-part mould (cope, cheek and drag) can be treated similar to those in a two-part mould.

The 3D model of the blade design was used to create the top and bottom(halves of the mould using Pro/Mold. Step joints (male & female) were created on the moulds for correct seating and location of the mould faces. A center support in a cylinder form was provided on the molds co-axial to the hub to facilitate between centers while machining the hub as shown in (*Figure.5*.) The feeding system and overflow provision, lettering and in gates to connect with the runner system were also incorporated in the mould model as shown in (*Figure.6*)

Center support provision

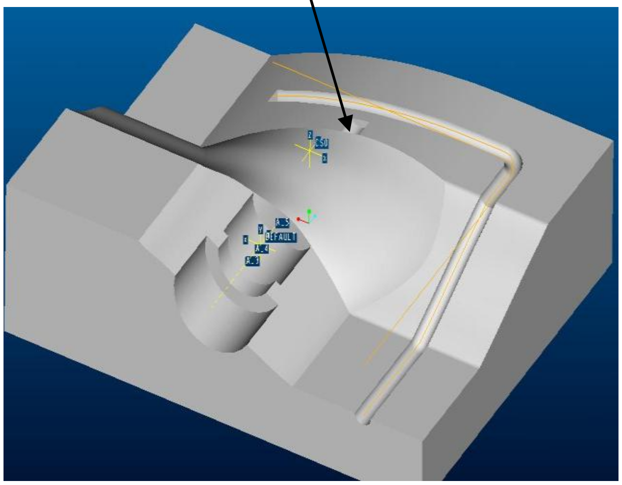

Figure.5
Top half of the mould

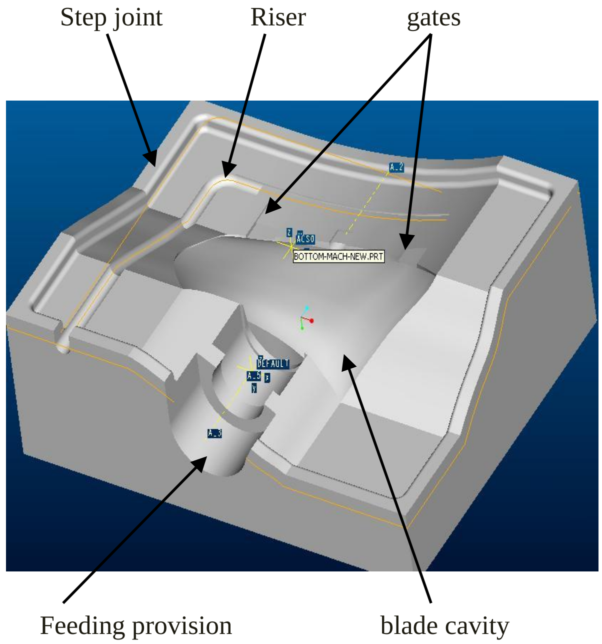

Figure.6
Bottom half of the mould

D. *Direct sand block milling*

The shrinkage allowance, feeding system and overflow provision, lettering and in gates to connect with the runner system were also incorporated in the mold model. The 'sand cavity boxes' were then further machined on a specific purpose CNC high speed machine(*Figure.7*) with specially developed tooling by CTI, exclusive for sand mold machining using Pro/Manufacturing module.

Figure.7
CMS –Poseidon specific purpose 5-axis CNC Machine used for machining sand moulds

E. *Final machining Stage*

After painting, the cope and drag were positioned accurately in the step joints and the mould was closed and the molten metal poured. After fettling (*Figure.8*) and heat treatment the blade was machined first on turning center for hub diameter and O-ring grooves and then on a CNC 4-axis horizontal machining centre (HMC) with rotary table on the top profile radius concentric with the casing diameter with standard clearance as shown in (*Figure.9.*) 3D CAD data became the basis for generating the cutter path. As the modeling was done in Pro/E, there was zero percent data loss while using the model in manufacturing module.

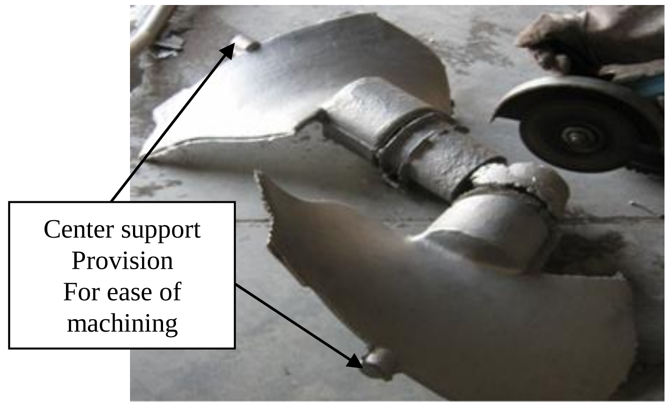

Figure.8.
Cast blades being cleaned (Fettling)

Figure.9. Top radius profile machining on 4-axis HMC

The blade after final machining is shown in (*Figure.10*). After the casting, the diffuser was heat treated, and subjected to liquid penetrant to detect surface breaking defects. Later the diffuser was machined to original dimensions.

After metrology validation, the re engineered blades were assembled for functioning.

All the machined dimensions were observed to be within the limits.

The average deviation of the blade profile on either sides were observed in the range of -0.617 to +0.327mm for and between +0.428 to +0.824 mm respectively.

The re-engineered blade surface was digitized to check the variation on the profile and the results were well within the limits as specified by the client.

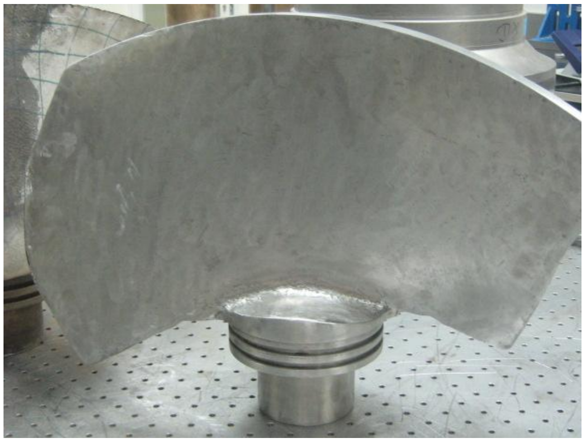

Figure.10.
Blade after final machining

Figure.11. Blades ready for assembly

III. COCLUSION

Reverse engineering is a process that can reduce the product development cycle time especially when there are no drawings or outdated and no further supply from the vendor. In the future this application is going to impact and penetrate the market. For contact type method with touch probes CMM is the ideal measuring equipment. Another faster method which is termed as non contact method using laser scanning is an alternative that can save more time and cost in the long run despite high initial investment as compared to contact method. Further the disadvantages of non contact method is huge file size, the point cloud should to trimmed and optimized to the desired boundary limits and difficult in controlling the points. Another important aspect is laser scanning cannot be used on reflecting and mirror surfaces.

The RE data available makes a faster shape metrology control of patterns, prototypes for foundry by comparing and calculating the deviation between 3D-digitized\scanned data and developed 3D-CAD model, before proceeding further with manufacturing foundry processes.

The pattern less process approach enables for rapid casting by eliminating patterns making process there by reducing the pattern making time, cost, storage and inventory. Any changes in design can be responded instantly as the changes can be easily updated in the backup 3D CAD model, and the casting process can be started directly from sand block machining as per the updated design.

The integration of CAM\CNC enables for faster manufacturing of any complicated shaped sand moulds, reducing the time as compared to conventional method of pattern making that relies totally on the skill of pattern maker to make a template of the complicated profile to match the patterns

The Reverse Engineering data enhances the metrological accuracy in product development and for foundry processing technology thereby sustaining the market competitiveness. The integration of RE and pattern less process with CAD\CAM\CNC technologies reduces lead-time and associated costs in foundry industry.

- If digitizing data is converted into datum curves/curves while digitizing itself, 40-50% of manual work can be reduced.
- Digitizing along and across directions on surfaces will improve the accuracy of surfaces.
- Accuracy in surfaces will depend on complexity of the profile and the skill of the CAD engineer. The accuracy of surfaces will increase by manipulation of surfaces.

In brief from this case study, it can be concluded by employing the above discussed applications the lead time for casting process can be reduced from nearly 17 weeks to 8 weeks as compared to the conventional method of casting.

Blade development	**Conventional casting(approximate)**	**Casting by CAD\CAM\CNC & Pattern less process**
Respond to design changes	3 weeks	1 day
patterns & cores design	2-3 weeks	Not required
Fabricate patterns and core boxes	4 -5 weeks	Not required
Designing gating system	1 week	1 day
Fabricate moulds	3 weeks	5 days
Diffuser casting	2 days	2 days
Machine ,inspection and assemble	2 weeks	2 weeks
Dye/liquid penetrant testing	2weeks	2weeks
Total time	**17 weeks**(considering minimum weeks)	**7 weeks**

Table-2

Lead time comparison for blade manufacturing

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