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3D Printing Enabled Rapid Manufacture of Metal Parts at Low Cost

Himanshu Khandelwal, *PhD Research Scholar*

Dr. B. Ravi, *Institute Chair Professor*

Mechanical Engineering Department,
Indian Institute of Technology Bombay, Mumbai

Abstract - Rapid prototyping and manufacturing based on additive technologies herald a paradigm shift in the production of small intricate parts directly from their CAD models. These technologies range from low-cost 3D printing using plastics, to high-end laser sintering of metal powders. The metal additive manufacturing systems are however, very expensive, making this route uneconomical for conventional applications. In this paper, we present an alternative route combining three relatively new yet low-cost processes: plastic 3D printing, no-bake molding, and direct casting. The 3D printer uses a spool of plastic wire passing through a heated nozzle mounted on x-y drive to fabricate a plastic pattern layer by layer from its solid model. Using this pattern, a sand mold block is fabricated by chemically-bonded no-bake system. The direct casting unit is a computer-controlled table-top induction furnace with provision for inserting a mold block. Molten metal emerges from the bottom of the crucible and enters the mold, minimizing air contact. The entire system been developed indigenously. It is compact, clean, safe and easy-to-operate. An Al-alloy impeller part taken up for capability demonstration took less than 10 hours to produce from its CAD model. Its dimensional accuracy and surface roughness were found to be significantly better than conventional sand casting. This system may also be considered for implementing in schools and colleges, providing an early and exciting exposure to rapid manufacturing for the young generation.

Keywords: Metal casting, additive manufacturing, rapid prototyping, tabletop foundry.

1. Introduction

Metal parts can be manufactured by mainly three routes: *subtractive* (machining), *forming* (casting, forging, powder metallurgy), or *additive* (3D printing, laser sintering) (Fig.1). The subtractive route implies material wastage; whereas the forming route requires part-specific tooling (dies and molds). These two limitations are overcome by additive manufacturing, which allows a complex shape to be produced directly and automatically from its 3D CAD model, usually within hours, using computer-aided technologies [1,2,3]. Most of these systems produce plastic parts, which are useful for prototyping: to check the form, fit and function. If the parts are fabricated in metal and can be directly used in end-applications, such as tooling or replacement parts, then this process is referred to as Rapid Manufacturing. In general rapid prototyping and manufacturing systems are suitable and economical for small intricate parts quickly required in small numbers. Relevant work in this field is briefly reviewed next.

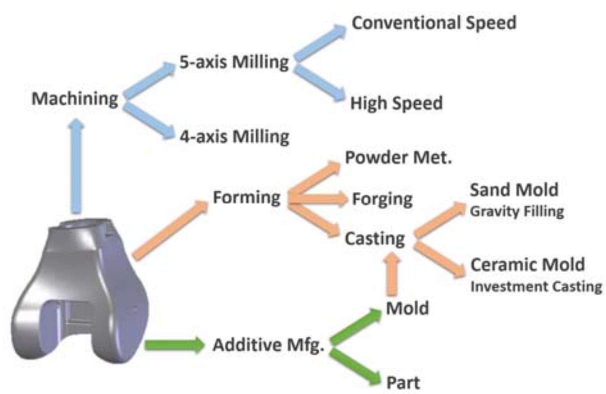

Fig. 1: Various manufacturing routes for a metal part (medical implant)

2. Previous and Related Work

Metal additive manufacturing is among the most recent developments in rapid manufacturing technologies (Fig.2). It usually involves a high-power energy source (laser or electron beam), which selectively melts metal powder, layer by layer, to create the final part. The high cost of these systems currently justifies their use only for critical applications like patient-specific medical implants (dental, orthopedic) and replacement parts for aerospace and defense applications [4]. A roadmap for additive manufacturing suggests the importance of integrating it with design, process modelling and process control [5]. These developments are also catalyzing relevant research in material science, hybrid manufacturing processes, and business models [6].

Fig. 2: Additive manufacturing systems for metal parts (top) and plastic parts (bottom)

Plastic additive manufacturing, more popularly called rapid prototyping (RP), can also be used to produce metal parts through the casting route. The most widely used approach is to fabricate a wax pattern on a RP machine, and use it for investment casting, eliminating the need for wax injection die [7]. If the parts are required in large numbers, then the wax injection mold itself can be fabricated using additive technologies [8]. The major issue is with investment casting process, which requires a number of steps (wax pattern, tree, shell-making, drying, preheating, metal pouring, and shakeout) along with the related equipment and a high level of skill-set to achieve the desired quality.

Plastic as well as metal additive manufacturing can also be used for fabricating the tooling (patterns and core boxes) for conventional sand casting process. While plastic tooling can be used for a few hundred cycles of molding before wearing off, the metal tooling can be used for several thousand cycles of molding and can justify their initial high cost [9,10]. The application of additive manufacturing technologies for producing cast parts is often termed as rapid casting [8], bringing in a revolution in age-old casting process.

In an earlier project, E-Foundry and TREELabs of IIT Bombay developed a tabletop induction furnace coupled with direct bottom pouring into a mold block prepared using no-bake process [11]. This was used to conduct several research experiments to study the fluidity of Al and Zn alloys, and to generate solidification cooling curves [12]. The effect of binder content on the dimensional quality of cast parts was studied, to optimize the mold composition [13].

This paper presents a hybrid route for rapid manufacturing of metal parts combining 3D printing with no-bake molding and direct casting. The steps are described in detail next, illustrated by an impeller cast part.

3. Rapid Casting System

The entire process chain for rapid casting system is shown in figure 3. The starting point is a 3D model of cast part created using a solid modelling program. This is imported into a casting design and simulation system for methods design. The as-cast model is sent to a plastic 3D printer. The plastic pattern is placed in a mold frame, into which silica sand mixed with chemical resin, hardener and accelerator is packed. After a few minutes, the pattern is pulled out, and the mold block is inserted into the tabletop furnace for pouring. After shakeout and cleaning, the casting is inspected using 3D scanning and microscopy.

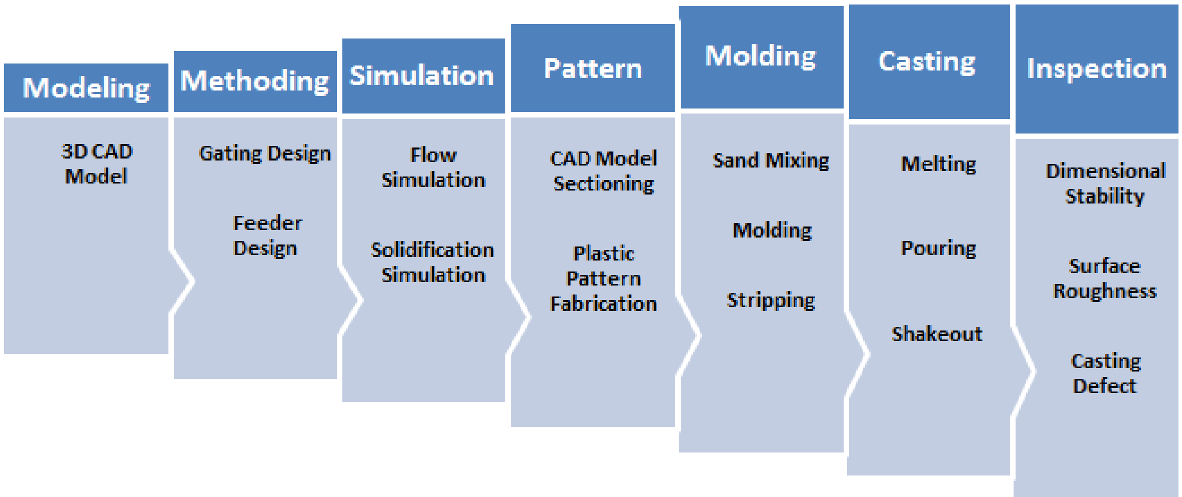

Fig. 3: Rapid casting system process chain

3.1 3D Modelling, Methoding and Simulation

The first step is to create a 3D CAD model of the cast part. The part selected to demonstrate the proposed system is an impeller, with a diameter of 80 mm and height 20 mm. It has six curved ribs, with varying thickness (3 mm to 1 mm), converging toward a central boss of diameter 20 mm. The part was modelled using CollaboCAD software (Fig. 4), which was developed by the CAD group of National Informatics Centre, New Delhi, led by Dr. Savita Dawar. This is a parametric feature-based 3D modelling software with online collaboration facility, and can be used to create models as well as assemblies. The software is based on Open Cascade graphics kernel. Its cost is less than half of other mainstream CAD programs available today. After solid modelling, the impeller part is exported as an STL format file for downstream applications.

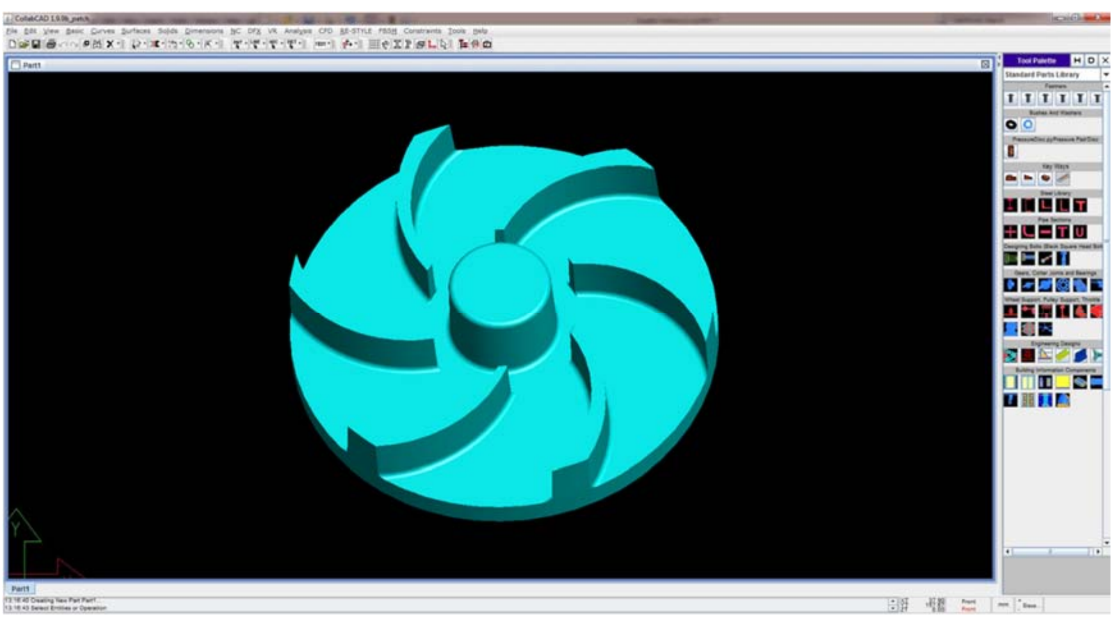

Fig. 4: Solid modelling of impeller in CollabCAD program

The next step is to convert the part model into a casting model. For this purpose, the impeller model is imported into the award-winning casting design software AutoCAST-X1, developed by 3D Foundry Tech, Mumbai, with research inputs from E-Foundry group of IIT Bombay, led by Prof. B. Ravi. The model is oriented so that the ribs are in the drag, ensuring better quality. The size of the mold box was taken as 250 x 140 x 120 mm. Aluminum alloy LM6 was selected as the part metal from the comprehensive database. A sprue was designed in the center (opposite the boss), to fill as well as act as a feeder.

Then mold filling and casting solidification were simulated using FLOW$^+$, a software module developed by the CSIR-NIIST Lab, Trivandrum, by a group of three scientists: Dr. Roschen Sasikumar, Dr. Savithri Sivaraman, and Dr. Elizabeth Jacob. This module has been tightly integrated with AutoCAST-X1. The integrated system provides a comprehensive range of functionality unavailable in any other casting software available today, and yet the cost of simulation per casting is a fraction of that using imported programs.

The total volume comprising the mold as well as the casting was automatically divided into 12.56 million cells, followed by application of the relevant boundary conditions such as the metal-mold interfacial heat transfer coefficient taken from the database. The pouring temperature was set as 720 ^{0}C. Figure 5 shows the results of flow simulation, solidification simulation, and shrinkage porosity prediction. Other quality measures, including air entrapment and cold shut also did not show any internal defects.

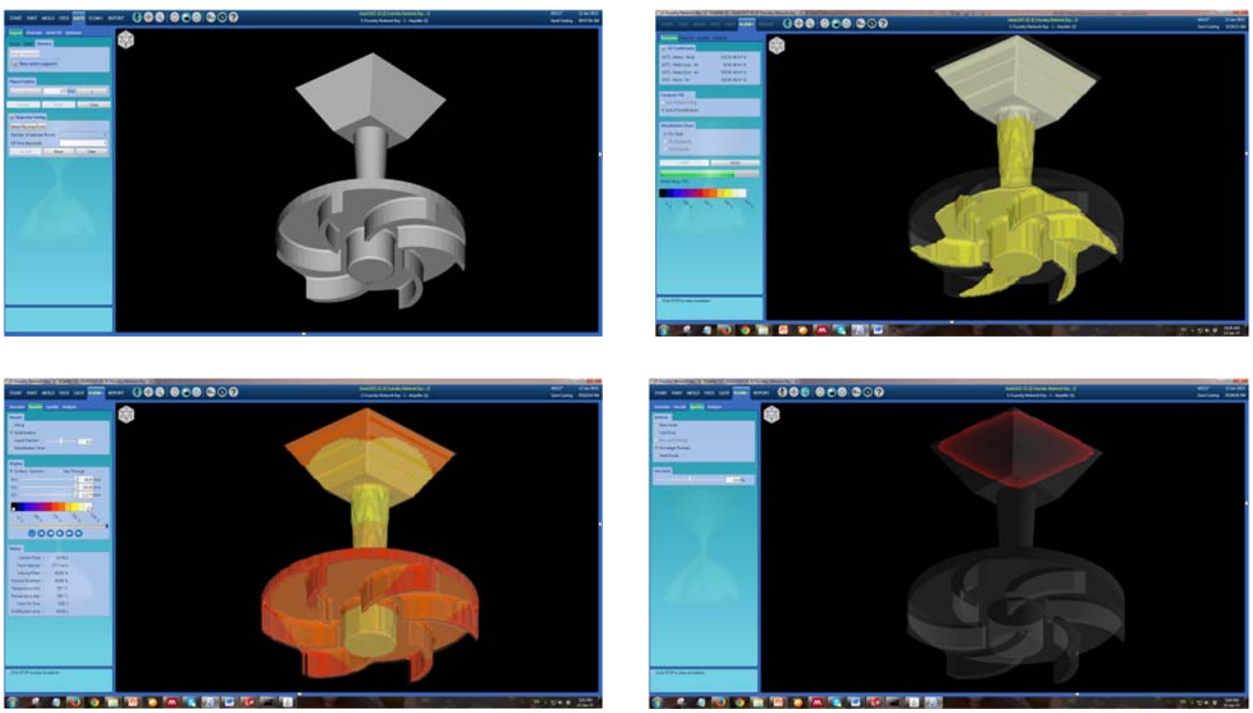

Fig. 5: Casting design and simulation using AutoCAST-X1 and FLOW$^+$

3.2 Pattern Printing and Mold Fabrication

The 3D CAD model of the impeller is sent to a tabletop 3D printer for fabricating the plastic pattern (Fig. 6). The 3D printer used in the present work is called RapidBot, indigenously developed by MakeMendel, Mumbai, established by Mr. Rasik Patel, alumni of Mechanical Engineering Department of IIT Bombay. This is among the most economical 3D printers, with both initial cost and running cost (material) being a fraction of that of high-end machines.

The CAD model (STL file) is first processed offline in a computer containing an open source slicing software Cura, which generates the G-code file containing the part cross-sections and cross-hatching motion of the 3D printer. This file is copied into an SD card, which is inserted in the card reader attached to the printer. The printer has a spool of plastic wire, which is pushed by an extruder into a heated nozzle. Semisolid plastic comes out of the nozzle and gets deposited on a platform. A controller moves the nozzle head in horizontal (X) direction, and the platform in horizontal (Y) direction. After the completion of a layer, the nozzle is moved in vertical (Z) direction. The layer thickness is 0.1 mm and the printing speed is 60 mm/s. Parts of size up to 220 x 220 x 165 mm can be fabricated. A mechanically stable design coupled with high quality liner motion guide provides good dimensional accuracy. The PLA bio-plastic wire is made from renewable natural resources and is biodegradable, but is strong enough to be used as pattern for the no-bake process. The impeller took about 6 hours to fabricate.

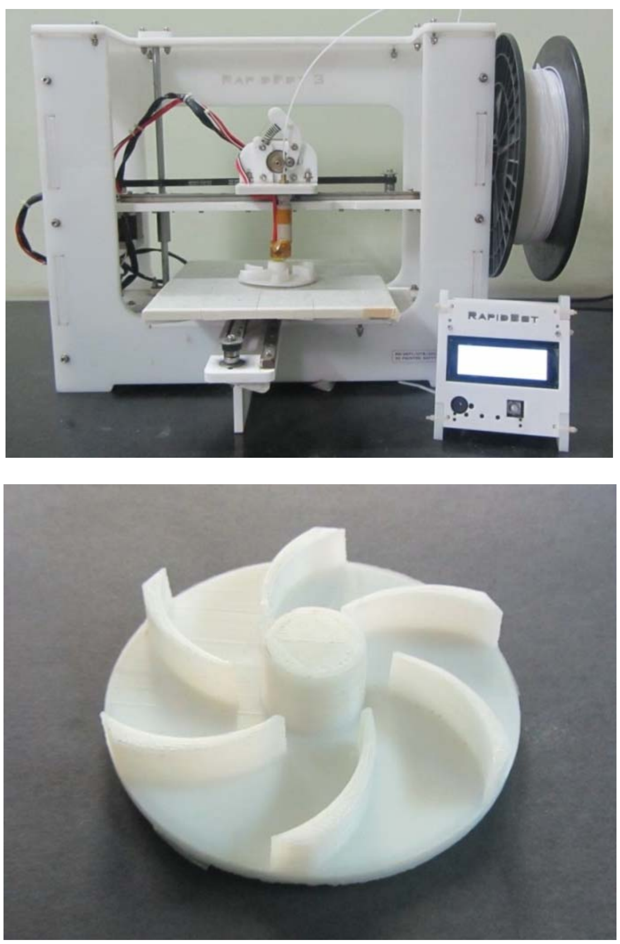

Fig. 6: 3D printing of impeller pattern using RapidBot

The proposed process employs chemically-bonded no-bake system for fabricating sand molds. This is a three part system, where part I (primary binder) is an alkyd oil urethane resin, part II is liquid amine catalyst and part III (secondary binder) is a polymeric MDI type isocyanate. Both part I and part III are dissolved in a special blend of solvent. The amount controls the rate of reaction between part I and part II. These chemicals were supplied by Gargi Industries, Mumbai.

The typical composition of the mixture used to prepare the no-bake molds is as follows: part I is 2% of sand; part II is 10% of resin; and part III is 20% of resin. A higher amount of catalyst as well as higher ambient temperature increases the strength of mold, but reduces the bench life of the sand mixture. For preparing the sand mixture, a three screen GFN 55-60 silica sand was first poured into a container and phenolic resin was added. After mixing for one minute, the polymeric MDI resin was added and mixed for another minute. The catalyst was slowly added to the sand mixture and mixed for about 30 seconds.

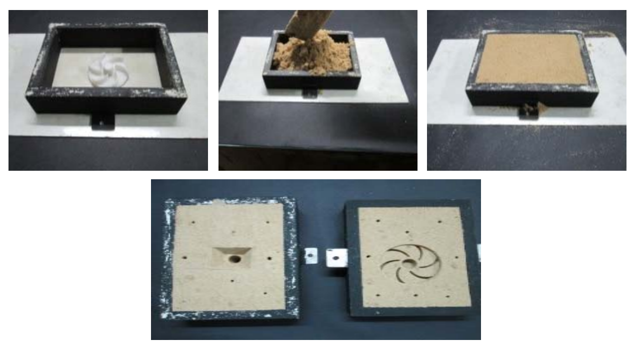

Fig. 7: Mold fabrication using resin binders supplied by Gargi Industries

The mixture of sand and binder was then transferred into two mold boxes corresponding to cope and drag (Fig. 7). The drag contains the impeller pattern, whereas the cope contains the sprue. The sand mixture only needs to be gently packed around the pattern; there is no need for ramming. The mixture sets within a few minutes, after which the pattern is stripped from the mold. The entire operation including mixing, molding, pattern stripping takes about 30 minutes, after which the mold was allowed to cure and further harden for another two hours. The cope and drag halves are assembled to obtain the mold ready for casting. Overall, this process was found to provide high moldability coupled with adequate hardness of mold during casting, and good collapsibility during shake-out.

3.3 Metal Melting and Direct Pouring

A single unit combines induction melting of metal and direct pouring into mold placed below the crucible. This award-winning innovative tabletop furnace called Melt-IT was developed by Dr. Dipankar in the TREELabs of IIT Bombay and marketed by Mobiclica, Mumbai. Heat is produced by eddy current generated by a high frequency alternating field. This unit combines the induction circuit, controller, coil, crucible, cooling water container and pump in a compact configuration (less than 400 mm width x 300 mm depth x 400 mm height), a fraction of the size of industrial induction furnaces. The furnace is able to melt 1 kg of Al-alloy in less than 30 minutes, using standard 220V, 5A power supply. High energy efficiency is obtained by using advanced control strategies, algorithms and sub-systems for delivering high quality metal melting conditions. This is expected to give much lower cost of melting per kg compared to industrial induction furnaces of comparable capacity.

Fig. 8: Metal melting and direct pouring using Melt-IT tabletop furnace

Figure 8 shows the tabletop furnace in which the mold is inserted below the graphite crucible. Once the metal reaches the pouring temperature (720 °C), the plug at the bottom of crucible is pulled (using a vertical rod), and molten metal directly enters the pouring basin of mold cavity. This ensures clean metal (free of slag), as well as minimal oxidation, moisture pick-up and heat loss. After about 30 minutes, the mold is broken to remove the cast part. Since no ladling is involved, the process is safe for use even by students and novice engineers.

4. Casting Inspection

The proposed approach has the potential for rapid manufacture of complex shaped metal parts. The impeller part produced by the approach described above was inspected for dimensional quality as well as surface finish to enable comparison with other processes. The details are given here.

4.1 3D Scanning of Part Geometry

3D scanning, also called reverse engineering, involves three critical steps: digitizing, data segmentation and data fitting. The as-cast impeller was placed on a rotating table and scanned using Steinbichler COMET system (Fig. 9). It uses a structured light mono camera (5 MP) with a resolution of 0.018 mm, and provided an accuracy of 0.005 mm. About 5 million points on the part surface were obtained within a minute.

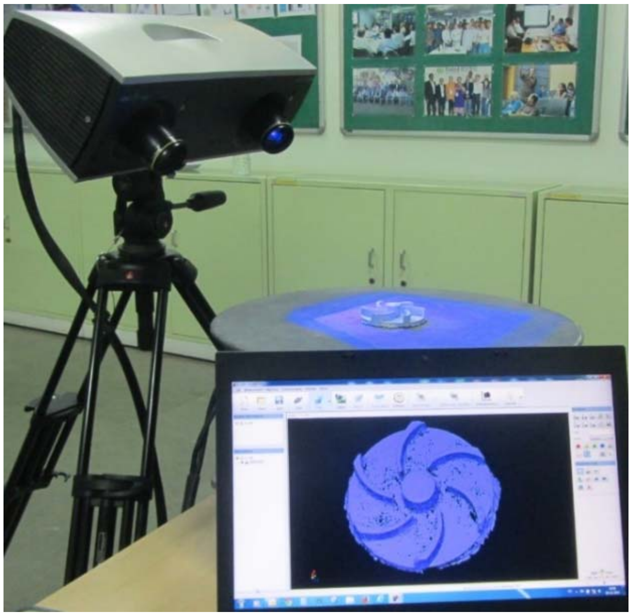

Fig. 9: 3D scanning of impeller casting

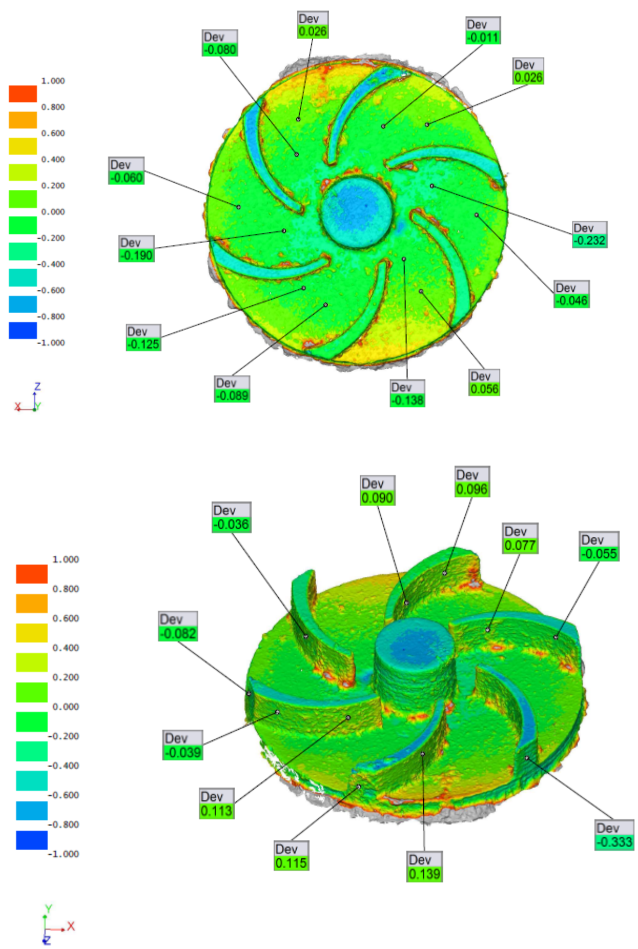

Fig. 10: Dimension deviation in horizontal (top) and vertical direction (bottom)

The cloud of points was processed by a software called Colin 3D, to obtain a surface model of the impeller. This is compared with the original CAD model of the part. The dimensional deviation between the CAD model and scanned data, in horizontal and vertical directions are illustrated in figure 10. The average dimensional deviation at flat surfaces of the part was found to be 0.075 mm, increasing to 0.1 mm on the ribs. There was more deviation in vertical direction compared to horizontal direction, which is a common observation in parts fabricated using additive manufacturing routes.

4.2 3D Microscopy for Surface Roughness

The surface roughness of the as-cast impeller was inspected using ZETA 20 3D optical microscope (Fig 11) installed in CEN Lab of IIT Bombay. This vertical scanning microscope generates 3D images of surfaces by acquiring a series of images at various heights, typically a few nanometers apart. At each height, the points on the surface that are in best focus are detected and their height and color is stored to recreate the final true color 3D image. Unlike typical scanning microscopes that are limited by the depth of focus of the objective lens, the Zeta microscope uses a unique optical design that enables a height resolution that is smaller than the depth of focus.

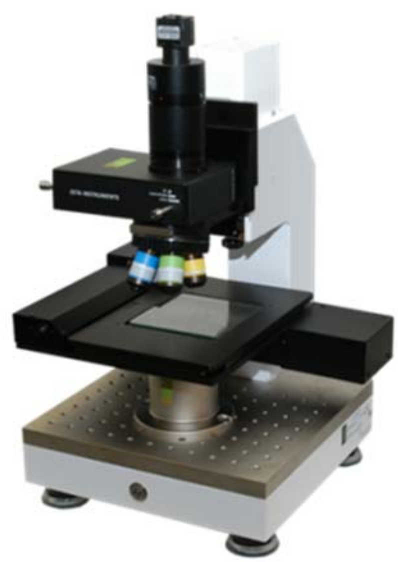

Fig. 11: 3D microscope (Zeta 20) used for surface inspection

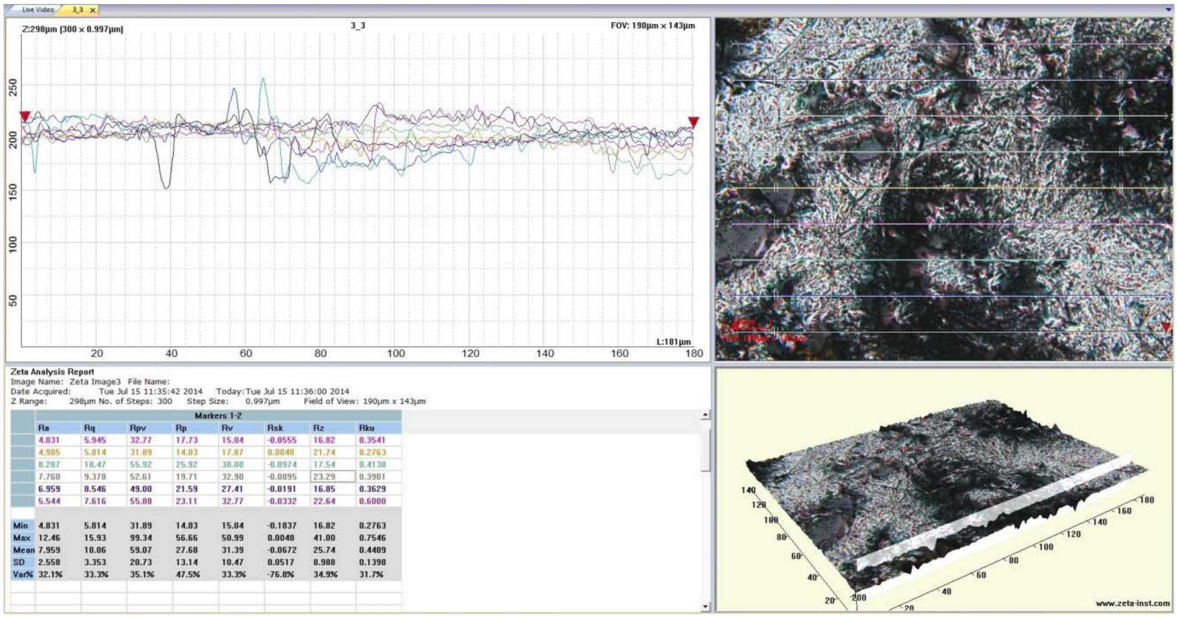

Fig. 12: 3D surface profile and roughness analysis

The middle of the circular boss, an area of 190 x 143 microns was observed using a 50 X lens of the microscope. This area is subdivided into 9 lines and the roughness values along these lines were measured in terms of pyramid height data (Fig. 12). The average surface roughness value (Ra) for the boss region of impeller casting was found to be 6.1 microns.

Finally, another casting of the impeller was also produced using CO2 molding, using similar sand grain size as that for no-bake molding, and inspected using the same microscope. The average surface roughness for this casting was found to be 13.05 microns, over twice that of that produced by no-bake molding.

5. Conclusion

In this work, a novel hybrid route for rapid manufacturing of metal parts has been evolved and successfully demonstrated for an impeller part. The route combines three indigenous low cost technologies: 3D plastic printing, chemically-bonded no-bake molding, and direct casting (induction melting + direct pouring). Starting from the 3D CAD model of the part, the casting was produced within 10 hours. 3D inspection of the part shape and surface showed good dimensional accuracy and surface finish, better than either green sand or CO2 molding process. All relevant equipment are compact; the process is quick, clean and affordable. It is highly suitable for rapid manufacture of one-off small intricate parts for prototyping and replacement purposes. It is also very useful for training a new generation of young engineers and enhancing their interest in manufacturing.

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MakeMendel, Mumbai for the 3D plastic printer *RapidBot*, and (e) TREElabs and Mobiclica, Mumbai, for the tabletop induction furnace *Melt-IT*. The assistance of research associates in E-Foundry lab, particularly K.H. Renukananda, Sandeep Gunjal and Vikas Karade in conducting and recording the casting experiments are also acknowledged.

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