Vacuum assisted casting of aluminum 6060 alloy using rapid prototyping pattern*

AM Kuthe[1*], SM Randiwe[2], SB Daronde[3]

[1*&,3]*Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur*

[2]*Shri Ramdeobaba College of Engineering and Management, Nagpur*

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ABSTRACT

The manufacturing of parts in aerospace and medical industries is most critical where materials of the part plays important role. The material composition of part decides the performance of part during the operation. The casting process is the only manufacturing process where innovative parts having non-linear geometries can be manufactured using rapid prototyping (RP) pattern. The CAD part can be directly converted into pattern (physical part) without human intervention and tooling using rapid prototyping and the design engineer is free from constraint from manufacturing. In this paper, the manufacturing of orthopedic implant using casting process is discussed where pattern is fabricated using rapid prototyping. Use of simulation software in casting viz. AutoCAST makes the otherwise complex process of casting much simpler and efficient. The medical implants are manufactured using the biocompatible metals like SS 316L, Co- Cr alloy. The Titanium is most preferred metals in medical implants as it is more biocompatible than SS 316 L and Co- Cr Alloy. The stress shielding effect is also not observed in Titanium made implant because of low modulus of elasticity compared to SS 316L and Co-Cr alloy. One of the major issues in the casting of medical implant is oxidation of metal during melting and pouring. The vacuum assisted casting is the only solution while using casting as the process of manufacturing for medical implant. The authors of the paper carried out the casting of part using vacuum for aluminum alloy 6060. The work will be further extended to biocompatible metals. The in-house induction furnace, having capacity of 5 kg is modified for meting and pouring unit in vacuum. The 500 LPM double stage direct drive rotary high vacuum pump is used for creating vacuum. The bottom pouring arrangement is used for pouring the molten metal in mould. The trial is successfully carried out for casting the part with and without vacuum. The result of as cast part using vacuum is very much promising compared to as cast part without vacuum. The biocompatible materials will be used for casting with vacuum which will help in designing the patient specific medical implants.

1. Introduction

The manufacturing of the part like orthopedic medical implant and part used in aircraft is not generally considered by the foundries in India as it involves high precision and quality. The resources required for manufacturing the said product are more and competition from imported part is very stiff. As the orthopedic medical implant are fitted in the patient body and being the Class III medical device, the part is required to pass stringent quality standards. The major lacuna in Indian foundries is absence of knowledge of casting simulation and inability to use new technique like Rapid prototyping. The imported medical implant is expensive and not affordable to common man in India. The unwillingness of Indian foundry to enter in this domain, push the prices of imported medical implant on higher scale. The government is interfering in the price matter.

But the immediate step to upgrade Indian foundries for manufacturing such high quality products is required.

The simulation of casting process using software like AutoCAST and use of Rapid prototyping in the process of manufacturing is the need of an hour.

*Corresponding author,
E-mail: amkme2002@yahoo.com (Dr. A. M. Kuthe)

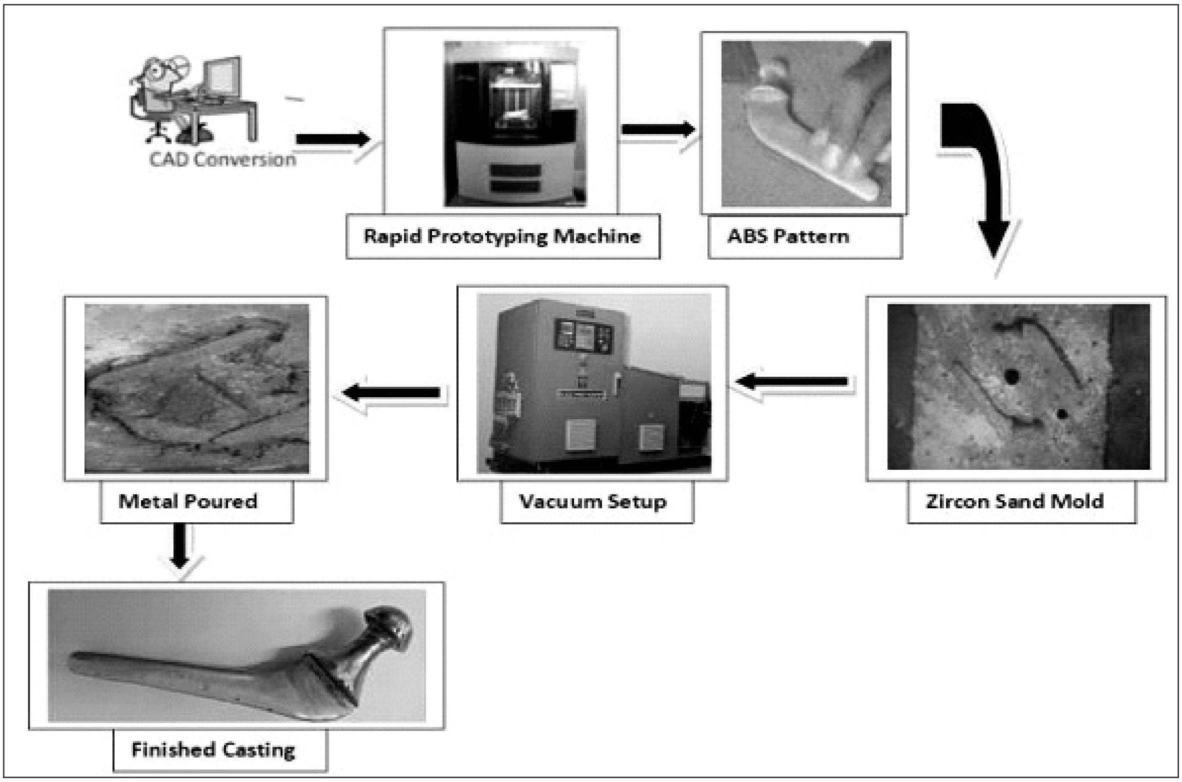

Fig. 1. A generalized standard methodology for the development of customized product (medical implant) using vacuum and sand casting method.

The simulation software decides the parameter to be set during the casting process so that the as cast product is defect free. The RP process can be used for getting the physical part viz. pattern or die from Computer Aided Design (CAD) model without human interference and tooling. Generalized standard workflow of process for the development of customized product (medical implant) with the low-cost vacuum facility is illustrated in Fig 1.

2. Methodology

2.1. Fabrication of pattern using RP

The pattern building using RP is now well-established method but many foundries in India are not willing to work in this field because of absence of manpower with knowledge of 3D modeling software in foundry and unwillingness to recruit such people. The medical implant is intricate product with many non-linear features in its geometry. The part can be easily drafted on computer using 3D modeling software and same can be converted into physical part i.e. pattern, using RP process [1]. The conventional pattern making process is unable to cope the challenge of handling the customization of part and also non-linear geometrical features of the part. The pattern thus obtained using RP process can be used to prepare the mould and then follows the molten metal pouring in the mould. The parameters for fabrication of mould and molten metal pouring can be set as per simulation software. The input for the simulation software is the 3D modeling of the part in STL format. The as-cast part is defect free as the complete process of casting is controlled by the simulation software.

2.2. Vacuum casting

Vacuum casting is a casting process for elastomers using a vacuum to draw the liquid material into the mold. This process is used when air in casting is a problem. Presently this process is very expensive. It is highly versatile technology capable of producing part for medical grade implant. The proposed setup in this paper for the casting of aluminium under vacuum was designed and developed in-house. Induction furnace is used for melting of aluminium and moltan metal directly poured with the help of bottom pouring crucible mechanism into mold. The pattern used for mold making is made on rapid prototype machine having material acrylonitrile butadiene styrene (ABS). A promising new technique for direct melting and pouring of aluminium alloy for medical implants emerged from this study. This research demonstrated the feasibility of direct melting and casting of the aluminium alloy 6060 vacuum technology. [5]

3. Experimentation

3.1. The experimental set up for RP assisted pattern making

The CAD model of the implant with the allowance is prepared in 3D modeling software and STL file is sent as input to RP machine to get the pattern. Refer Fig. 1 and Fig 2. The customization of implants (i.e. consideration of neck shaft angle, vertical offset, horizontal offset as per patient anatomy) is possible by RP assisted pattern making [2].

From the CAD model of implant with added allowances STL file is generated which is shown in Fig 3.

Fig. 2. CAD model of implant.

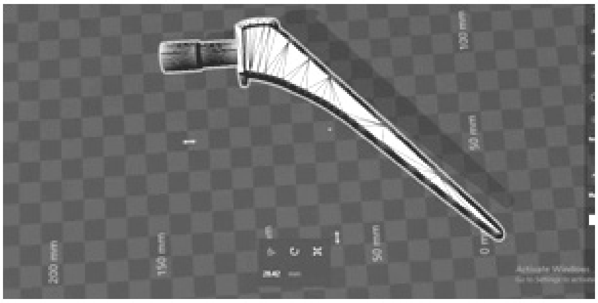

Fig. 3. STL model of implants.

Allowances added: 2.5% of the length or volume to be added.
Shaft length before adding allowance: 137.5mm
Shaft length after adding allowance: 140.98mm
Length of small cylinder before adding allowance: 17 mm
Length of small cylinder after adding allowance: 17.35 mm
Length of large cylinder before adding allowance: 15 mm
Length of large cylinder after adding allowance: 15.3 mm

Additional machining allowance of 1-1.5mm is added to the surface and other miscellaneous allowances are dimensionally insignificant.

The Auto CAST software is used to get the mould layout and gating design analysis (Refer Fig 4). The data generated using AutoCAST is shown in table 1.

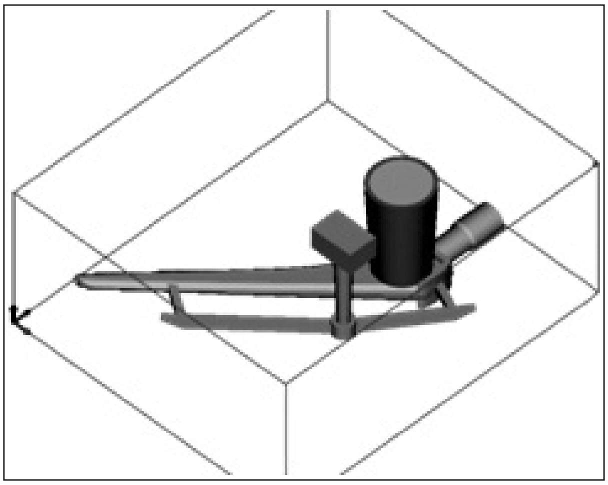

Fig. 4. Model layout, gating and riser designed from AutoCAST.

Table 1
Data generated from AutoCAST.

Layout Name	Implant Final	Date & Time	02 Oct 17, 2.39 PM
Cast Metal	Cast Steel-St Low C	Casting process	Sand Casting
Density	7672kg/m^3	Liquids	1493 C
Order quantity	1000	Yield	43.31%
PART			
Dimensions	102.21X138.31X14 (in mm)	Part Surface Area	69.63 cm^2
Min. Thickness	1.38mm	Max. Thickness	11.97 mm
Part Weight	141.73g	Part Volume	18 cm^3
MOLD			
Mold material	Ceramic Sand	Density	1550 kg/m^3
Dimensions	170mm×200mm×140mm	Parting Orientation	Horizontal
Cavities	X	Draw Distance	7 mm
Min. Cav. Wall gap	63 mm	Metal/Sand weight	5.52%
Min Cav. Cav. gap	NA	Metal/Sand volume	1.09%
FEEDERS			
Total Feeder Weight	201.47g	Feeding Yield	42.59%
FEEDER-1			
Orientation	Top	Shape	Cylindrical
Weight	201.47g	Volume	25.59 cm^3

Diameter Top	25 mm	Diameter Bottom	18 mm
Height	61.74 mm	Number of Necks	1
NECK-1			
Shape	Cylindrical	Length	4 mm
Diameter at Part	12 mm	Diameter at feeder	12 mm
GATING (OVERALL)			
Pouring Temp.	1640 °C	Mold Filling Time	NA
Total Metal Head	70 mm	Avg. Fill Rate	0 mg/s
Gating System Wt.	93.98 g	Gating Yield	61.4 %
Total Poured Wt.	402.93 g		
SPRUE			
Pouring Basin Shape	Rectangular	Pouring Basin Dimensions	20X20 X10 (in mm)
SPRUE PARAMETERS			
Shape	Cylindrical	Height	70 mm
Top Diameter	10 mm	Bottom Diameter	6 mm
SPRUE WELL			
Diameter	10 mm	Height	6.99 mm
GATES			
No. of Gates	3	Total Gate Area	48 mm^2
Total Gating Weight	5.67	Total Gate Volume	719.73 mm^3
PARAMETERS FOR GATES 1,2 &3			
Shape	Rectangular	Length	16.57, 25.98 & 15.95 (in mm)
Height	4, 4 &4 (in mm)	Width	4, 4 & 4 (in mm)
RUNNERS			
No. of Runners	2	Total Runner Area	48 mm^2
Total Runner Weight	10. 16 g	Total Runner Volume	1.29 cm^3
PARAMETERS FOR RUNNERS 1&2			
Shape	Rectangular	Length	37.58 & 55.55(in mm)
Height	4 & 4 (in mm)	Width	4 & 4 (in mm)

Fig. 5. RP Pattern fabricated on 3D printing machine.

The RP pattern Fig 5 is fabricated on 3D printing machine using STL file develop from CAD model is shown in Fig 5.

3.2. The experimental set up for vacuum assisted casting

3.2.1. Vacuum chamber design

Fig 6 show a conceptual CAD model of the setup designed and fabricated for pouring the molten metal. The vacuum chamber is suitable for ferrous and non- ferrous metal. The completed system comprises of the three main sub-system viz. bottom pouring mechanism, heating of the metal and vacuum system.

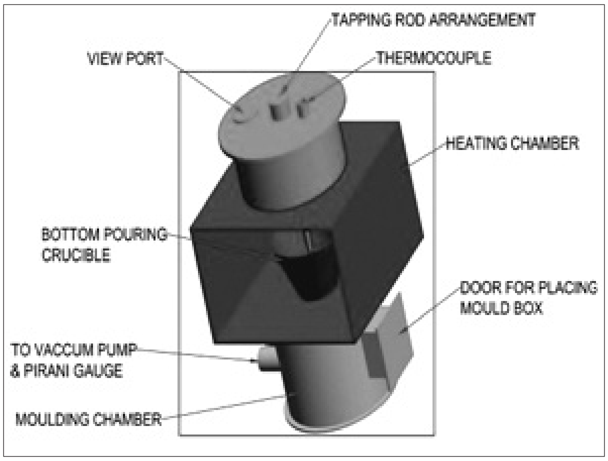

Fig. 6. CAD model of the setup.

A vacuum chamber is a rigid enclosure from which air and other gases are removed by a vacuum pump. These results in a low-pressure environment within the chamber commonly referred to as a vacuum. In low vacuum applications, chambers are sealed with elastomeric O-rings. Pressure vessel is designed which can sustain the vacuum level of 10^{-3}mm of Hg. pressure on the inner side of the chamber, while the outer surface is exposed to the atmosphere.

From ASME Design, Mild Steel and Stainless steel are selected for fabrication of vacuum chamber. Tapping rod chamber is made up of Stainless steel and melting chamber and mold placing chamber is made up of mild steel. Thickness of MS and SS metal sheets are 8 mm. Dimension of vacuum chamber are shown in Fig.7.

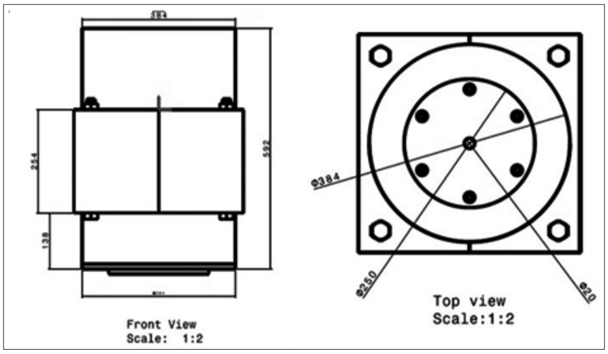

Fig. 7. Dimensions of front view and top of vacuum chamber (dimension are in mm).

Fig. 8 shows the modified vacuum chamber unit for the reactive material. This vacuum chamber unit is for both melting and pouring.

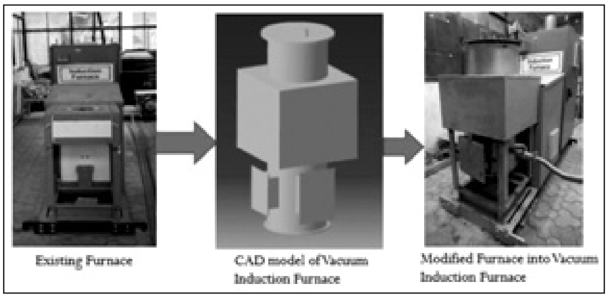

Fig. 8. Modification of existing induction furnace into vacuum induction furnace.

3.2.2. Vacuum pump

As metal is very prone to oxygen, the whole chamber must be free from the oxygen and any other gases. To evacuate vacuum chamber, we used vacuum pump of Model IVP 600 with electro mechanical anti suck back valve mounted at the inlet of the pump, displacement 50 Hz: 600 LPM and Ultimate Pressure range: < 1 x 10^{-3} torr with Gas Ballast Closed. Pirani gauge is used for measuring of pressure inside the vacuum chamber, specification of which is as follows-

Model DPRG-1GH, Display Range:0.001 To 1000 Mbar and dependable measuring range: 20 To 0.001 Mb. Fig. 9 shows vacuum pump and pirani gsuge.

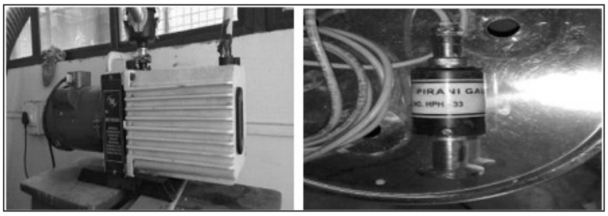

Fig. 9. Vacuum pump and pirani gauge.

3.2.3. Bottom pouring crucible mechanism

Fig. 10. Bottom pouring graphite crucible with tapping rod.

The specially designed bottom pouring graphite crucible used for the induction melting process. Fig. 10 shows specially designed bottom pouring graphite crucibles. Bottom pouring graphite crucible with rod is used to tap the molten metal from lower end of the crucible. Conventional tilting crucible was not suitable for pouring the molten metal. The molten metal is poured through the bottom of crucible using rod shown in Fig. 11. Nut is rotated for 2 to 3 pitch to lift the rod and pour molten metal in to the mold cavity. Pouring rate is maintained by Nut rotation.

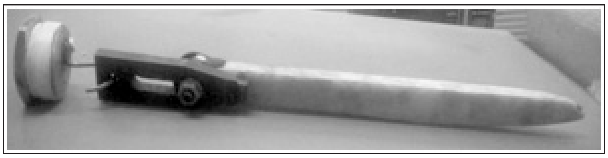

Fig. 11. Bottom pouring graphite crucible with tapping rod.

3.2.4. Experimental setup and standard operating procedure (SOP) of the system

A standard operating procedure is written below step-by-step instructions compiled to help operator to carry out routine operations.

Step 1. Charge the crucible with the desired material into the heating chamber. The material should be free from dust and dirt. Bottom pouring crucible and the tapping rod should be properly aligned with the molding box runner and riser, as the tapping of the molten metal is carried out from the bottom.

Step 2. Place the molding box of desired shape in the molding chamber and close the door. The top chamber is provided with door to observe the molten metal condition and to note the temperature of the molten metal.

Step 3. Switch on the vacuum pump and run it to achieve the desired the level of vacuum.

Step 4. Furnace should be operated once the vacuum chamber achieves the vacuum level. The reading can be noted from the pirani gauge digital indicator.

Step 5. As soon as material gets melted, lift the rod and tap out the material.

Step 6. The whole system of melting and pouring should be operated in the vacuum environment only.

Fig. 12. The Experimental set up with vacuum system.

Fig. 12 shows the experimental setup with vacuum system.

Fig. 13. As cast part: fabricated using RP

The preparation of mould as per the software, melting and pouring of molten metal (Aluminum alloy 6060) under vacuum was carried out in CAD CAM center of VNIT Nagpur and as cast part is shown in Fig 13.

4. Results

4.1. Evacuating the vacuum chamber

It is essential to evacuate the vacuum chamber before the experimentation. Fig. 14 shows the time required to evacuate the vacuum chamber with rotary vane pump having a capacity of 500 lit/min.

It was proposed to melt and test the casted sample of Aluminum with and without vacuum environment. The physical and chemical properties of the aluminum were studied.

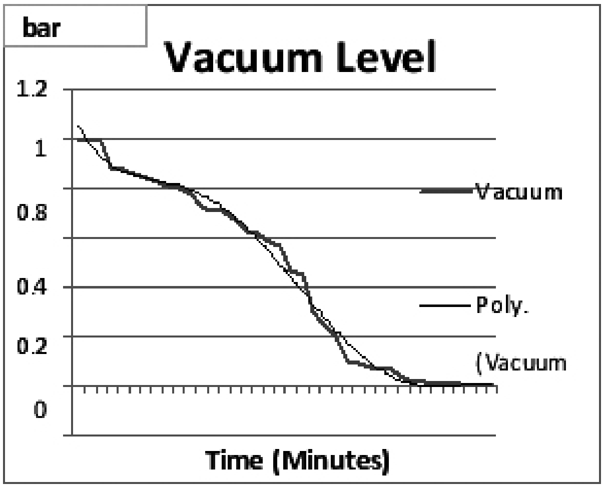

Fig. 14. Time required evacuating the chamber.

4.2. Experimental trials on aluminium casting

An experimental analysis is carried out on the aluminium alloy. The chemical composition of 6060 aluminum alloy given in Table 2 and weight of 250 g were induction melted in graphite crucibles in open atmospheric temperature.

The alloy was induction heated to a melt temperature of 760.3 °C and hold at this temperature for 10 minutes. Melted aluminum is poured into the mold and as cast part is obtained. As cast part is tested for chemical analysis in lab and the result of chemical analysis is shown in table 3. Similar experimentation is carried out with the vacuum induction Furnace. Instead of open atmosphere the aluminum alloy is melted in vacuum chamber. Vacuum chamber of induction melting furnace was evacuated to a vacuum pressure of 0.56 bar.

Table 2
Chemical analysis of AL6060 alloy.

Alloy 6060 Al	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zi	Residuals
Weight %	97.9-99.3	0.05 Max	0.1 Max	0.1 -0.3	0.35 - 0.5	0.10	0.3-0.6	0.1 Max	0.15 Max	0.15 Max

Table 3
Chemical analysis of AL6060 alloy melting in without vacuum induction furnace.

Alloy 6060 Al	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zi	Residuals
Weight %	85.291	0.0211	1.78	1.09	0.188	0.1709	1.558	0.0273	0.121	0.15 Max

Table 4
Chemical analysis of AL6060 alloy melting in vacuum induction furnace.

Alloy 6060 Al	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zi	Residuals
Weight %	98.175	0.0204	0.029	0.54	0.45	0.0436	0.6	0.156	0.114	0.15 Max

As cast part of vacuum induction melting is tested for chemical analysis and the results are shown in table 4.

5. Discussion

The manufacturing of part using RP pattern and vacuum assisted sand casting is thus possible for AL6060 Alloy. The result of chemical of the part casted using vacuum is very promising. The part having irregular geometries mostly used in medical implants can be manufactured using vacuum assisted casting.

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Dr. A M Kuthe, Professor, Department of Mechanical Engineering
Visvesvaraya National Institute of Technology, Nagpur
Specialization: Rapid Prototyping, Layered Manufacturing

Dr. Sanjay M Randiwe, Assistant Professor,
Shri Ramdeobaba College of Engineering and Management, Nagpur.
Specialization: Rapid Prototyping, Titanium melting and casting

Mr. Subodh B Daronde, Senior Research Fellow, CAD-CAM Centre,
Visvesvaraya National Institute of Technology, Nagpur