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Experimental and Analytical Analysis of Light Alloy Shell Castings Using Three Dimensional Printing

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ABSTRACT

Growth of rapid prototyping (RP) technologies has proven highly significant in efforts to reduce the production time for a number of casting processes. Lot of research has been done in production of sacrificial sand moulds used in investment casting. This paper systematically presents procedure of producing shell casting using light alloys in ceramic moulds created with three dimensional printing (3DP). The shells are made using special sand provided by Z-Corporation for production of easy and economical shell moulds with creation of 3D printers. Selected part was designed using UNIGRAPHICS modeling software. The moulds using the CAD model were produced with ZCorp 510 RPT machine. An experimental and analytical investigation was conducted to establish the influence of parameters like Layer thickness (Lt), Post curing time (Pc), orientation (O) for printing of shell. Light alloy shell castings using aluminium, zinc and lead were produced with the developed moulds. The effect of other parameters like the shell wall thickness (SWT), weight density (WD) and pouring temperatures (PT) on mechanical characteristics like hardness, dimensional accuracy and international tolerance (IT) grades of castings was also analyzed experimently. The paper concludes feasibility to reduce the shell wall thickness from 12 mm to 2 mm with dimensional accuracy. Consistencies with the permissible range of tolerance grades were achieved. Further at optimised SWT 5 mm, 5 mm and 6 mm, production cost has been reduced by 54.28%, 54.28% and 49.12% and production time has been reduced by 46.05%, 46.28% and 43.42% respectively in comparison to 12mm recommended shell thickness for selected light alloys.

Keywords: *Rapid Prototyping; Shell Casting; Three Dimensional Printing (3DP); Layer Thickness; Curing Time; Orientation; Dimensional Accuracy.*

1.0 Introduction

The prospective growth of RP technologies during the past decade has seen enormous changes in many traditional industrialized processes, either in terms of being able to employ rapid tooling techniques or attempt alternative improvements, leading to rapid manufacture in few cases. Casting processes were also influenced either in terms of expendable patterns being produced using one of the RP techniques [1], [2] or direct making of sand and metal shells using processes such as Selective Laser Sintering [3], [4], or process improvements achieved through integration of CAD [5],

Reverse Engineering and RP [6], [7]. Replacement of investment cast parts made by traditional time consuming methods and integration of the process with RP prototypes used as patterns was an obvious development, considering the common quality of both processes to be able to produce complex parts. The literature presents numerous attempts made in this direction, while the cost of materials and processing time still remain at large. The wide range of materials being processed by 3DP allowed the application of the technique in a variety of other ways, as a probable means of achieving rapid casting.

Mechanical and physical properties of mould samples made by laser sintering Lasercorn coated sand were investigated using the Taguchi method (Casalino et al. 2004).

While most research has focused attention on applying RP to casting seems to have directed towards SLS, 3D printing of shells by the ZCast process of Z Corporation, drew little attention. In fact, this process is relatively cheap and is very effective in direct printing of complex shells with a proprietary mould material.

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The process allows rapidly changes from a CAD file to a prototype metal part. While the technique offers unique solutions to situations requiring real metal prototypes as well as one-off parts to be readily produced, the essential characteristics of the process are still not investigated. In particular, the mould characteristics and the quality of castings produced are of significant interest for the effective design of shells in typical cases and the efficient application of the process for sound castings.

This paper is the result of an ongoing research that is aimed at establishing the essential characteristics of both shells and castings produced by using the 3D printing technology.

While the investigation of the casting quality and applicability of various coatings and economics of the process are still undergoing, this paper presents the results of experiments conducted to develop an understanding of the influence of the curing parameters on the properties of the mould material.

The optimum combination of the curing time and temperature for the best compressive strength and permeability of the mould material could be identified based on the mathematical models developed.

1.1 Three Dimensional printing (3DP) Techniques

In the current research the 3DP technology has been used as rapid shell casting to make the shell moulds. The process of 3DP was patented in 1994 under U.S. patent number 005340656 [8]. It was developed at Massachusetts Institute of Technology (MIT) based on inkjet technology [9] and licensed to Soligen Corporation, Extrude Hone and Z - Corporation of Burlington.

It is classified as a typical "concept modeler", a low-end system, and represents the fastest RP process [10]. [18] Facilitates the identification of appropriate rapid manufacturing (RM) process for a given situation and sets the framework for design for RM.

As shown in Figure 3, parts are built upon a platform situated in a bin full of powder material. Powdered material is distributed in the form of a layer at a time and selectively hardened and joined together by depositing drops of binder from a mechanism similar to that used for ink- jet printing.

Then a piston lowers the part so that the next layer of powder can be applied. For each layer, powder hopper and roller systems distribute a thin layer of powder over the top of the work tray. Adapted continuous-jet printing nozzles apply binder during a raster scan of the work area, selectively hardening the part's cross-section.

The loose powder that wasn't hardened remains, acts as a support for subsequent layers. The process is repeated to complete the part.

When finished, the green part is then removed from the unbound powder, and excess unbound powder is blown off. Finished parts can be infiltrated with wax, CA glue, or other sealants to improve durability and surface finish.

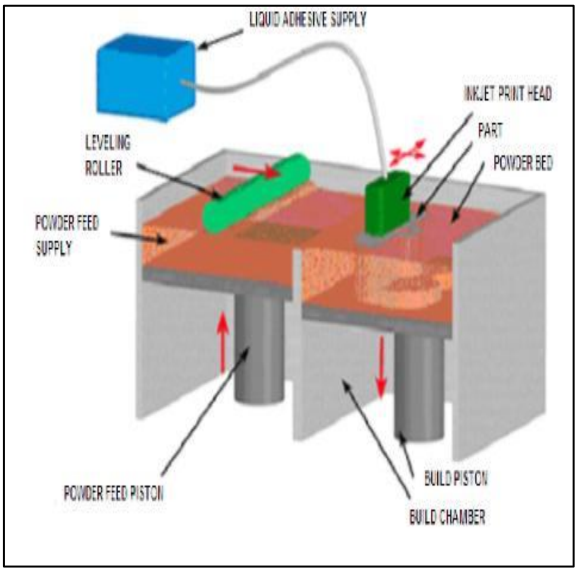
The present research aims at using the 3DP technology as rapid shell casting to make the shell moulds. An 'RP' shell mould was used as the positive pattern around which the sand is filled in a moulding box.

An effort has been made through experiments, to study the feasibility of decreasing the shell wall thickness from the recommended 12mm, in order to reduce the cost of production and time as well as to evaluate the dimensional accuracy, mechanical properties of the aluminum, zinc and lead alloy castings obtained for assembly purposes. While pouring the molten metal, shells have been supported by loose green sand for making sound castings.

The consistency of the tolerance grades of the obtained castings (IT grades) as per allowed IS standards for casting process were checked. [10] Conducted studies for two technological solutions in this field and the study aims at evaluating the dimensional accuracy of two rapid castings (RC) solutions based on 3D printing technology for investment casting starting from 3D printed starch patterns and the Z Cast process for the production of cavities for light-alloys castings. [11, 12] also proposed similar studies with regard to different solutions for the production of technological prototype. The present research appreciates the concurrent product, process development and production of a series of technological metal prototypes by means of a rapid casting process. The following objectives have been devised for the research work;

1. To validate the feasibility of decreasing the shell thickness from recommended 12mm in order to reduce the production cost & time.
2. To estimate the dimensional accuracy of the aluminium, zinc and lead castings obtained and to check the consistency of the tolerance grade of the castings (IT grade) as per allowed IS standards for casting.
3. Verification of perception, to present the perception in physical form with minimum cost and minise time.

Fig: 1. Three Dimensional Printing (3DP) Processes



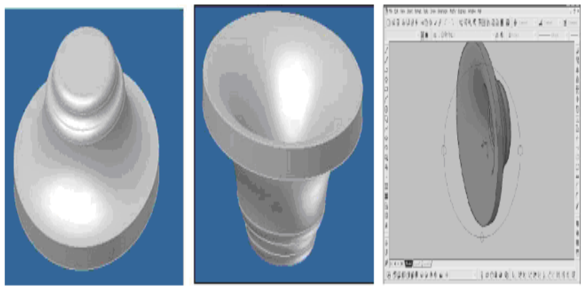
2.0 Design of Experiments and Methodology

To achieve the objectives, the materials like aluminum, zinc and lead, alloys were selected and used for critical analysis of castings.

The component chosen as a benchmark was representative of the industrial manufacturing field, where the application of the rapid tooling and rapid casting technologies is particularly relevant.

The experimental procedure started with the CAD modeling of the benchmark as shown in Figure 2 having a total volume of 20483.83 mm^3 and surface area of 9225.79 mm^2.

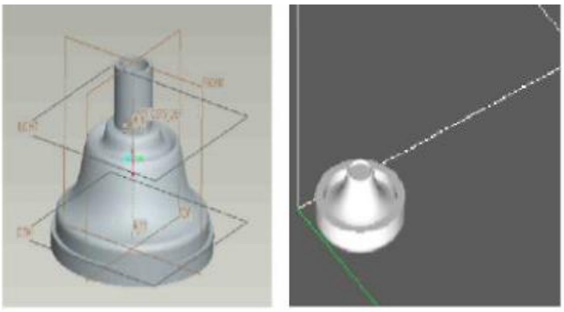
Fig: 2. Computer-Aided Design Model of the Casing Chosen as a Benchmark



The optimized combination was used for experimentation as the best setting of the machine. So for this best setting, experiment was conducted with the planning of following phases:-

1. After the selection of the benchmark, the component to be built was modelled using a CAD. The CAD software used for the modelling was UNIGRAPHICS Ver. NX 5. The analysis of benchmark leads to the definition of the feeding system and riser in a concurrent product process development [19].
2. The upper and lower shells of the split pattern were made for different values of the thickness. The values for the shells were 12, 10, 9, 8, 7, 6, 5, 4, 3, and 2mm. CAD modeling of Upper and lower shells and these parts were manufactured by 3D printing Technique. Fig 3 (a) and (b) shows the CAD model of the upper and lower shells, respectively, for 12mm thickness.
3. The CAD models of upper and lower shells were improved into the standard triangulation language format, also known as stereo lithography format.
4. The optimized combination of process parameters by using DOE and ANOVA for future final experimentation is 0.127mm layer thickness, 60 min post-curing time and horizontal orientation (HX).
5. Moulds were manufactured in 3DP with Z cast 501 powder and parts were heat treated at a temperature of 110^{0}C for 1 h.
6. The upper and lower shells were placed in such a way that the central axes of both the shells were co-linear.

7. **Fig: 3 (a). Computer-Aided Design Model of the Upper Shell and (B) Computer-Aided Design Model of the Lower Shell**



(a) (b)

3.0 Material and Methods

3.1 Selection of Materials for Making of Shell Mould

For casting, low temperature materials such as aluminium, zinc and lead, the selected material is the proprietary ZCast 501 powder developed by Z Corporation for a range of its printers as a mould material and is basically a plaster-ceramic composite.

When ZCast 501 powder used for making moulds on Z Corporation's Z510 (spectrum) three dimensional machine, the particles of the powder are in turn bonded together by means of the resin binder, ZB56 supplied by Z Corporation.

The printed moulds suffer from excessive moisture content and poor strength in the green state and require subsequent baking to remove excess moisture and for dry strength.

The mechanism of strengthening perhaps is the curing of the binder material and subsequent solidification to form the substrate for the powder particles to stick together.

Prolonged heating at low temperatures or use of excessive temperatures could result in the burning off of the low melting phases. Oven baking at 180 to 230^0C and for a period of 4 to 8 hours is suggested by Z Corporation, primarily as to drive off excessive moisture content.

While these appear to be quite wide ranges, it is also felt that baking with these two parameters varied at different levels would have a significant influence on the most essential characteristics of the mould, production cost and production time.

3.2 Selection of material for experimentation

Z-Cast process will be used to produce shell moulds of different shell wall thicknesses 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, and 2 mm for producing technological prototypes of benchmark with 50 mm diameter for three selected materials. In order to accomplish the objectives Aluminium, Zinc and Lead materials are choose as a benchmark, representative of manufacturing field for industrial application, where the application of rapid tooling and rapid casting technologies is particularly relevant.

3.2.1 Machine selected

To achieve the objective for Z-Cast Direct Metal Casting, Z-Corporation machine, Spectrum ZCorp 510 was used to produce shells for casting to investigate for optimizing the SWT from recommended 12 mm for the production of Aluminium, Zinc and Lead castings.

3.2.2 Shell mould prepared

After Selection of benchmark for prototype casting the modeling of shell moulds by using CAD software UNIGRAPHICS Ver. NX5 was done for manufacturing of shell moulds of 50 mm diameter with different shell thicknesses in 3DP using ZCast process.

3.2.3 Shell casting

ZCast Direct Metal Casting is a rapid casting solution uses ZCast 501 powder and Z56 binder for the shell casting of light alloys. The ZCast process creates the shell molds directly from CAD data by using 3DP technology. ZCast501 powder is a blend of foundry sand, plaster and additives, consolidated in the 3D printer by selective jetting of a vinyl resin [Bassoli 2009]. Conventionally, metal castings are produced by using the sand casting tooling, techniques and procedures. With respect to traditional sand casting, limited by the pattern extractability, layer by layer construction allows obtaining complex part, without any restrictions in terms of undercuts provided only that the unconsolidated powder can be removed from the cavity [14]. It eliminates the pattern creation phase of the traditional sand casting process in a revolutionary way, resulting in a drastic reduction of casting the lead time from weeks to days [15]. Major features of ZCast process are:

Table: 1. Effect of Layer Thickness, Curing Time and Orientation as Pilot Experiment

Layer thickness (mm)	Part orientation	Post curing time	Production time (min)	Production cost (Rs)
0.101	Horizontal	60 minutes	100	1335
0.127	Horizontal		76	1144
0.101	Vertical		135	1645
0.127	Vertical		170	1417

- ZCast501 mold is recommended for non ferrous light alloy with pouring temperature below 1100 C
- The recommended shell mold wall thickness range is 12 mm (minimum) to 25.4mm (maximum) ZCast501 [16].
- Before pouring, ZCast moulds must be baked in an oven from 1800C to 2300C for between 4 and 8 hours (based on volume), until it is "bone" dry.
- Customers cast the metal into these 3D printed molds for prototype evaluation or fully functional parts

The best settings of the 3DP machine in terms of layer thickness, part orientation and post curing time, upper and lower shell prototypes were produced by using pilot experiment. Numbers of experiments were conducted for the possible outcomes of the 3DP machine with objective function of minimizing the production cost, production time and improvement in dimensional as well as mechanical properties.

Post treatment for parts was chosen as standard specifications (6 hrs isothermal at 200°C, heating rise of 1.5°C).

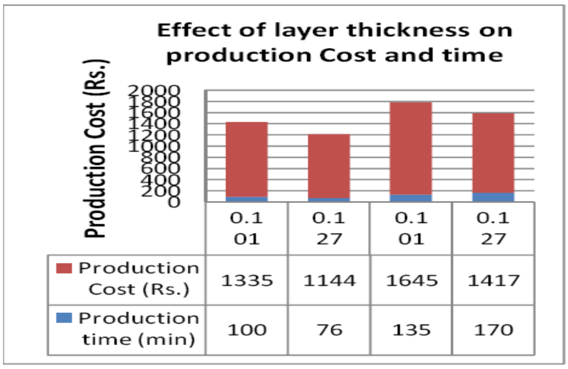
3.2.4 Development of prototype for different shell thicknesses and production of castings

Starting from the CAD model of the component, shells were modeled for different shell wall thicknesses.

From the analysis of geometry and volume of benchmark, single feeder and riser system were designed for pouring the molten metal. RP shell models are used as positive patterns around which the sand is filled in a molding box. Light alloys like aluminium alloy, Zinc alloy and lead was used for casting.

The observation of the pilot experimental study as shown in Table 1 and leads to the selection of layer thickness as 0.127 mm and horizontal part orientation for the final experimentation with constant post curing time of 60 minutes as shown in Fig 4.

Fig: 4. Effect of Layer Thickness, Part Orientation on Production Cost and Time



4.0 Observations and Calculations

The measurement path for the internal and the external surfaces of the benchmark has been generated through the measurement software of the GEOPAK v2.4.R10 CMM. These paths direct the movements of CMM probe along trajectories normal to the parts surface. About 75 points have been measured on the external surface. For each point the machine software evaluates the deviation between the measured positions and the theoretical ones for the X, Y and Z coordinates. Table 3 shows the variation in measured dimension of the average outer diameter, average outer curve radius and average thickness and hardness of casting prepared with respect to shell wall thickness (mm).

The different dimensions measured with CMM are outer diameter, curve radius and component thickness. Outer diameter was measured as ten circles mean diameter at different points. The curve radius was measured by scanning the inner and outer curve surfaces. The observations of the dimensional measurements have been used to evaluate the tolerance unit (n) that derives starting from the standard tolerance factor i, defined in standard UNI EN 20286-1 (UNI EN 20286, 1995).

The values of standard tolerances corresponding to IT5-IT18 grades, for nominal sizes from 3mm to 500mm, are evaluated considering the standard tolerance factor i (in micrometers) indicated by the following formula, where D is the geometric mean of the range of nominal sizes in millimeters.

Tolerance factor $i = 0.45 (D)^{1/3} + 0.001D$, ---------- (1)

In fact, the standard tolerances are not evaluated separately for each nominal size, but for a range of nominal sizes. For a standard nominal dimension D_{JN}, the number of the tolerance units 'n' is evaluated as follows:

$n = 1000(D_{JN} - D_{JM})/ i$, --------- (2)

Where D_{JM} is a measured dimension.

The tolerance is expressed as a multiple of i: for example, IT14 corresponds to 400i with n= 400. The results of dimensional measurements are used to evaluate the tolerance grades. The classification of different IT grades according to UNI EN 20286-1 is shown in table 2. The value of tolerance unit's 'n' was calculated for each value of measured dimension of casting, the latter taken as a reference index for evaluation of tolerance grade. The results of dimensional measurements are shown in Figure 5 and Figure 6. The results of dimensional measurements are used to evaluate the tolerance grade. The observed tolerance grades are IT14 and IT15 as presented in table 6 to table 8 and shows that the results are consistent with the values allowed for casting operations between IT11 and IT18 [17]. All observations are within the range of IT grades and thus are completely acceptable at all shell wall thickness from 12 mm to 2 mm. However, better dimensional accuracy is observed at 5 mm, 5 mm and 6 mm shell wall thickness for aluminium, zinc and lead alloys respectively as shown in figure 5 to figure 7. It should be noted that the process of solidification at different thermal gradients, which affects the heat transfer and finally shrinkage of the casting.

Fig: 5. Effect of Shell Wall Thickness on Outer Diameter for Aluminium Alloy

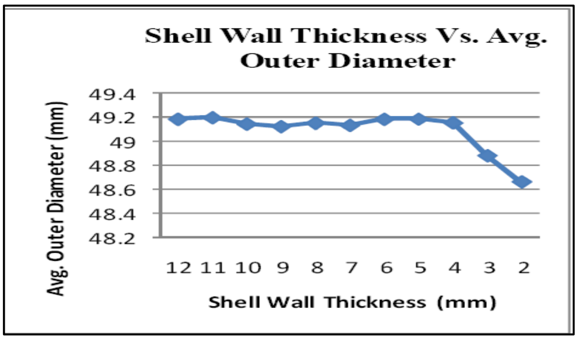


Fig: 6. Effect of Shell Wall Thickness on Curve radius for aluminium alloy

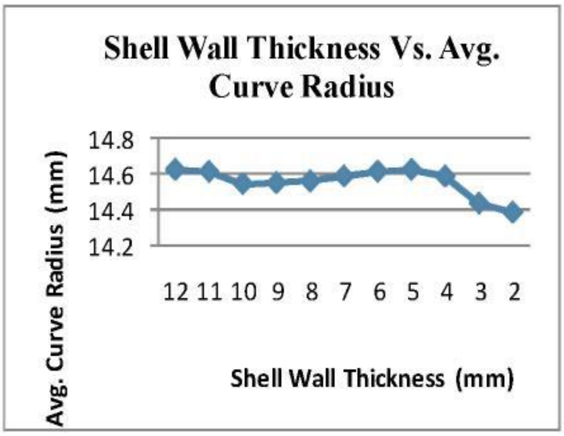


Fig: 7. Effect of Shell Wall Thickness on Surface Hardness for Aluminium Alloy

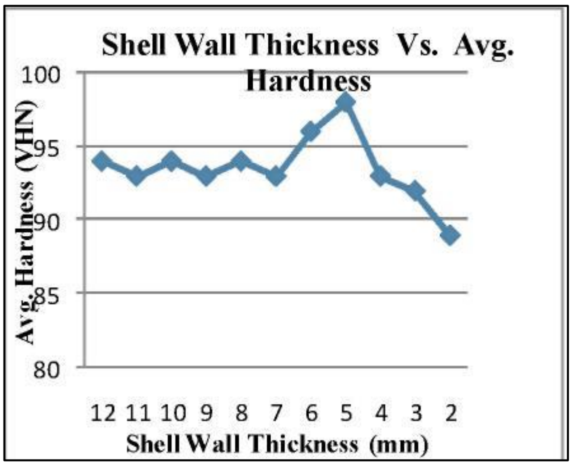


Fig: 8. Effect of Shell Wall Thickness on Outer Diameter for Zinc Alloy

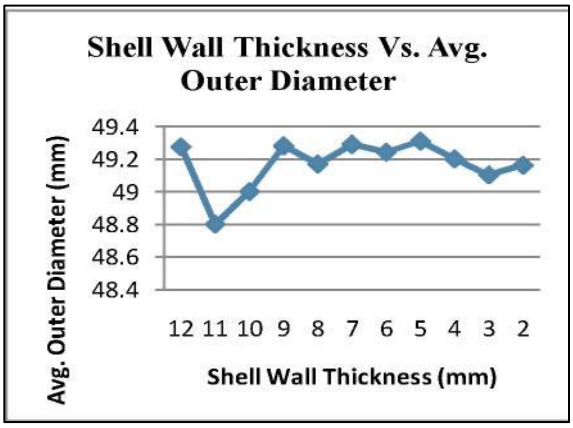


Fig: 9. Effect of Shell Wall Thickness on Curve Radius for Zinc Alloy

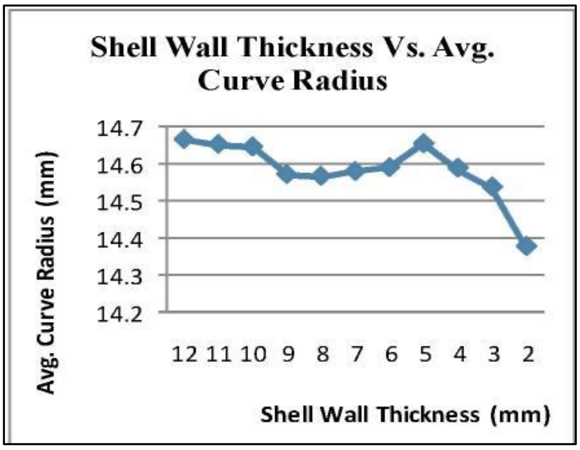


Fig: 10. Effect of Shell Wall Thickness on Surface Hardness for Zinc Alloy

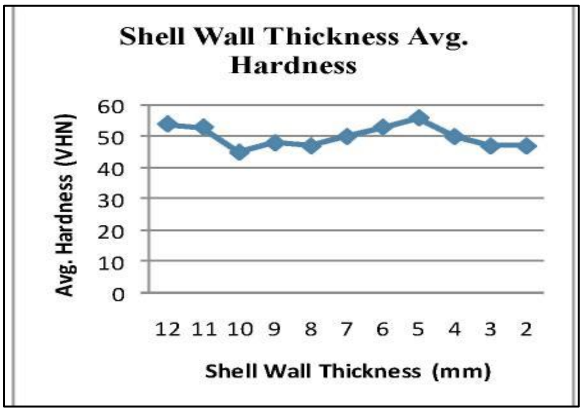


Fig: 11. Effect of Shell Wall Thickness on Outer Diameter for Lead Alloy

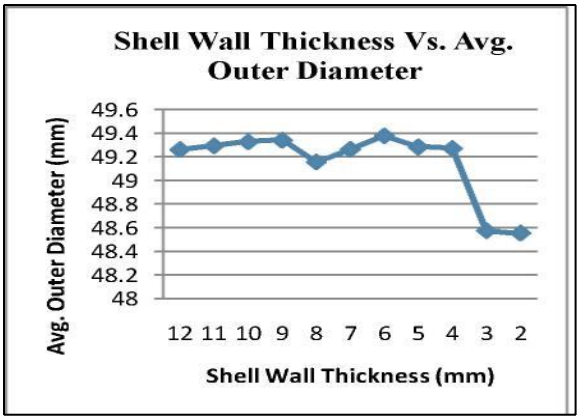


Fig: 12. Effect of Shell Wall Thickness on Curve Radius for Lead Alloy

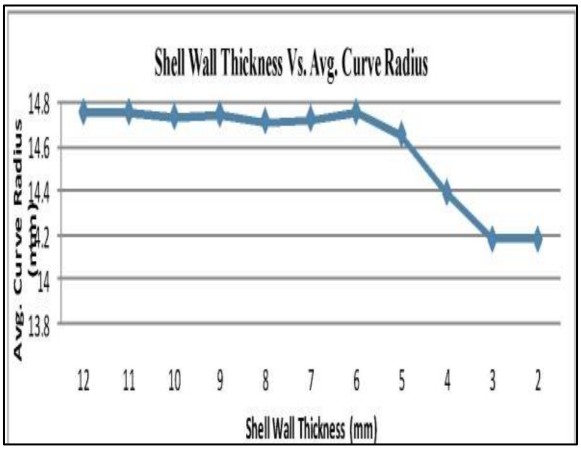
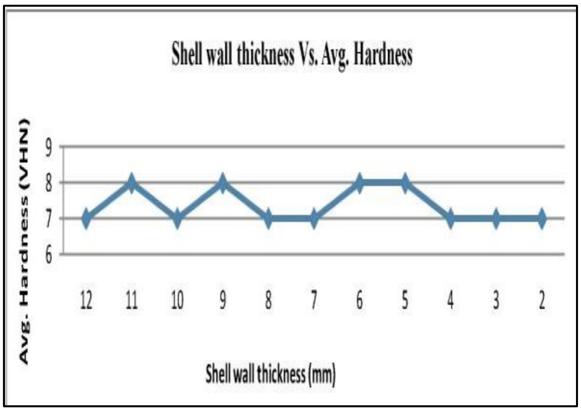


Fig: 13. Effect of Shell Wall Thickness on Surface Hardness for Lead Alloy



Calculation for Production Cost and Production Time

The cost for shell mould can be found out as:

For 12mm shell thickness:

Powder consumption = 5.27 cubic inches (86359.83 cubic mm)

Powder cost = 4300 for 1 kg

Powder Cost for 12mm shell = Rs. 419

Binder Consumption = 51.8 ml.

Binder Cost = Rs.14000/lt

Binder Cost for 12mm shell = Rs. 725

Hence Total Cost for shell mould = Rs. 419 + 725 = Rs. 1144

Similarly, the cost for other thickness was found.

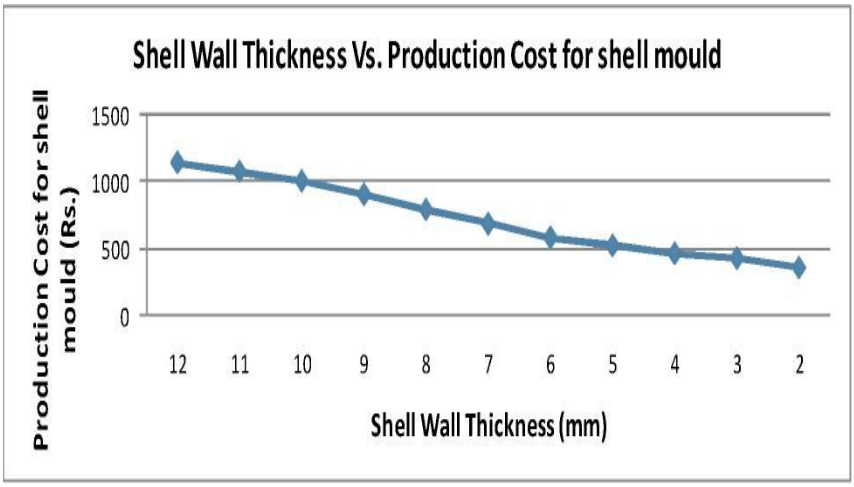
Table: 2. Better Dimensional Accuracy for Aluminium, Zinc and Lead Alloys W.R.T. Experiment Number

Light alloy	Experiment Number	Shell Wall Thickness (mm)	Avg. Outer Diameter (mm)	Avg. Curve Radius (mm)	Avg. Thickness (mm)	Avg. Hardness (VHN)
Aluminium	8	5	49.1871	14.624	3.239	98
Zinc	8	5	49.3131	14.654	3.294	56
Lead	7	6	49.3816	14.75	3.3698	8

Table: 3. Observations of Shell Wall Thickness for Production Cost and Production Time

Experiment Number	Shell Wall Thickness (mm)	Powder Consumption (Cubic in.)	Cost for Powder (Rs.)	Binder Consumption (ml)	Cost for Binder (Rs.)	Production Cost for shell mould (Rs.)	Production Time for shell mould (min)
1	12	5.27	419	51.8	725	1144	76
2	11	4.99	397	48.6	680	1077	69
3	10	4.78	380	44.7	626	1006	64
4	9	4.42	352	39.5	553	905	60
5	8	3.92	311	34.3	480	791	52
6	7	3.34	266	29.9	418	684	49
7	6	2.73	216	26.2	366	582	43
8	5	2.18	172	25.1	351	523	41
9	4	1.64	131	23.9	334	465	40
10	3	1.42	113	22.5	315	428	38
11	2	0.91	73	20.3	284	357	35

Fig: 14. Effect of Shell Wall Thickness on Production Cost for Shell Mould



Calculation of Dimensional Accuracy and Tolerance Grades

(i) Outer Diameter as Dimension of Component

$D = (30 * 50)^{1/2} = 38.73$mm

Tolerance factor (i) = $0.45\ (D)^{1/3} + 0.001D$,

$= 0.45\ (38.73)^{1/3} + 0.001(38.73) = 1.58\ \mu m$ (ii) Curve Radius as Dimension of Component $D = (10 * 18)^{1/2} = 13.42$mm Tolerance factor (i) = $0.45\ (D)^{1/3} + 0.001D$, $= 0.45\ (13.42)^{1/3} + 0.001(13.42) = 1.08\ \mu m$

Fig: 15. Effect of Shell Wall Thickness on Production Time for Shell Mould

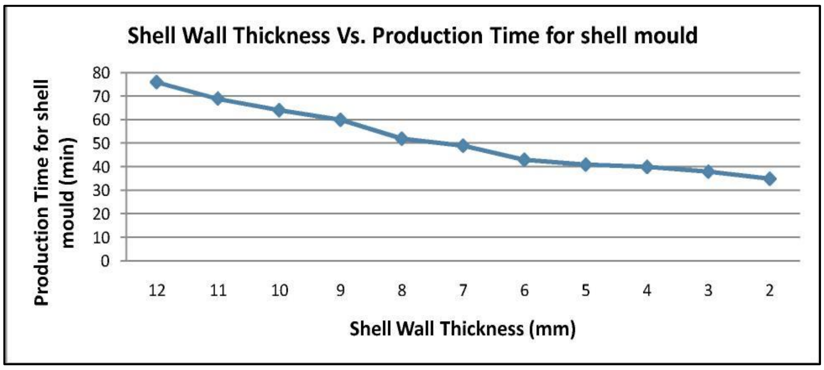


Table: 4. Class of Different IT Grade w.r.t. Outer Diameter for Aluminium Alloy

Experiment Number	Shell Wall Thickness (mm)	Outer Diameter as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		D_{JN}	D_{JM}			
1	12	50	49.1868	1.58	514.6836	IT14
2	11	50	49.1983	1.58	507.4051	IT14
3	10	50	49.1457	1.58	540.6962	IT14
4	9	50	49.1254	1.58	553.5443	IT14
5	8	50	49.1536	1.58	535.6962	IT14
6	7	50	49.1338	1.58	548.2279	IT14
7	6	50	49.1863	1.58	515	IT14
8	5	50	49.1871	1.58	514.4937	IT14
9	4	50	49.1555	1.58	534.4937	IT14
10	3	50	48.879	1.58	709.4937	IT15
11	2	50	48.659	1.58	848.7342	IT15

Fig: 16. Effect of Shell Wall Thickness on Tolerance Grade W.R.T. Outer Diameter

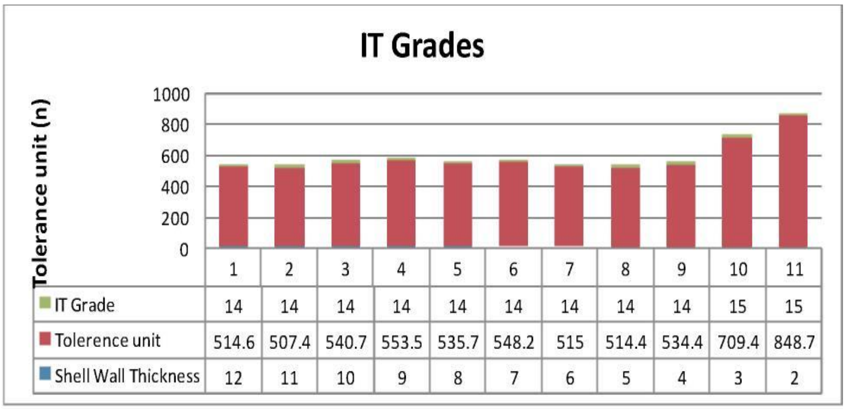


Table: 5. Class of Different IT Grade w.r.t. Curve Radius for Aluminium Alloy

Experiment Number	Shell Wall Thickness (mm)	Curve Radius as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		D_{JN}	D_{JM}			
1	12	14.9	14.625	1.08	254.6294	IT14
2	11	14.9	14.612	1.08	266.6664	IT14
3	10	14.9	14.545	1.08	328.7034	IT14
4	9	14.9	14.551	1.08	323.1478	IT14
5	8	14.9	14.561	1.08	313.8886	IT14
6	7	14.9	14.588	1.08	288.8886	IT14
7	6	14.9	14.612	1.08	266.6664	IT14
8	5	14.9	14.624	1.08	255.5553	IT14
9	4	14.9	14.588	1.08	288.8886	IT14
10	3	14.9	14.437	1.08	428.7033	IT15
11	2	14.9	14.387	1.08	474.9995	IT15

Fig: 17. Effect of Shell Wall Thickness on Tolerance Grade w.r.t Curve Radius

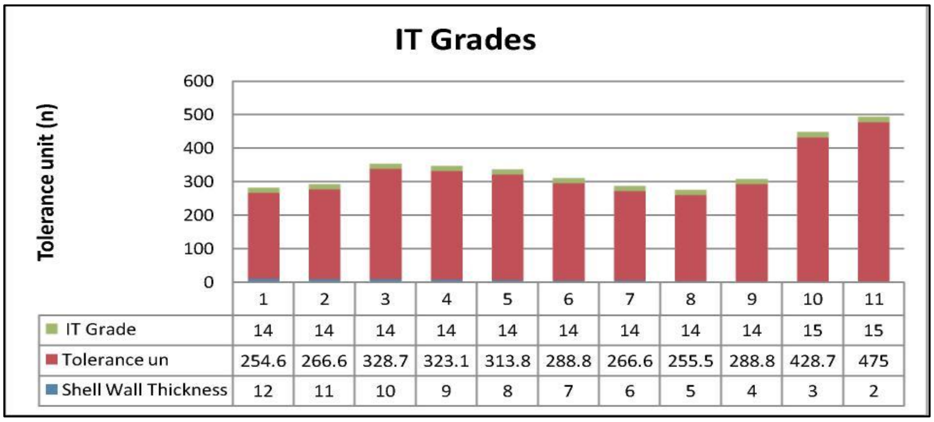


Table: 6. Class of Different IT Grade w.r.t. Outer Diameter for Zinc Alloy

Experiment Number	Shell Wall Thickness (mm)	Outer Diameter as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		DJN	DJM			
1	12	50	49.2774	1.58	457.3418	IT14
2	11	50	48.8012	1.58	758.7342	IT15
3	10	50	49.0021	1.58	631.5823	IT15
4	9	50	49.2829	1.58	453.8608	IT14
5	8	50	49.1717	1.58	524.2405	IT14
6	7	50	49.2931	1.58	447.4051	IT14
7	6	50	49.2455	1.58	477.5317	IT14
8	5	50	49.3131	1.58	434.7468	IT14
9	4	50	49.2037	1.58	503.9873	IT14
10	3	50	49.1051	1.58	566.3924	IT14
11	2	50	49.1655	1.58	528.1646	IT14

Fig: 18. Effect of Shell Wall Thickness on Tolerance Grade w.r.t. Outer Radius

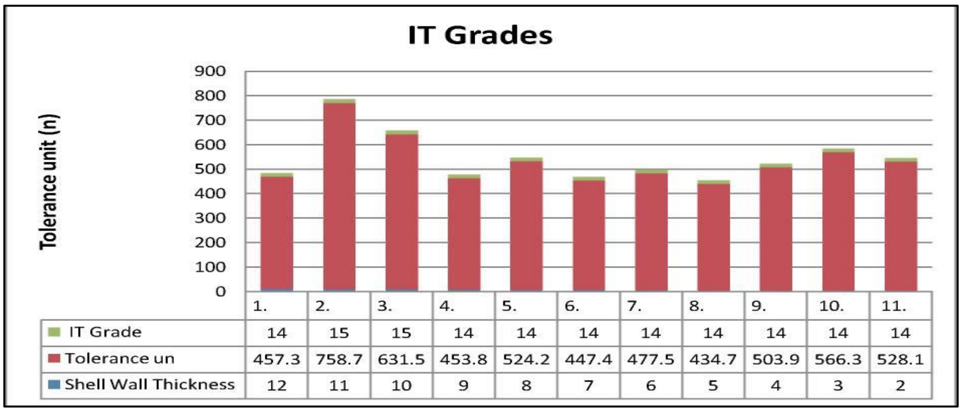


Table: 7. Class of Different IT Grade w.r.t. Outer Diameter for Zinc Alloy

Experiment Number	Shell Wall Thickness (mm)	Curve Radius as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		DJN	DJM			
1.	12	14.9	14.655	1.08	226.8516	IT14
2.	11	14.9	14.649	1.08	232.4072	IT14
3.	10	14.9	14.645	1.08	236.1109	IT14
4.	9	14.9	14.571	1.08	304.6293	IT14
5.	8	14.9	14.566	1.08	309.259	IT14
6.	7	14.9	14.579	1.08	297.2219	IT14
7.	6	14.9	14.629	1.08	250.9257	IT14
8.	5	14.9	14.654	1.08	227.7776	IT14
9.	4	14.9	14.588	1.08	288.8886	IT14
10.	3	14.9	14.537	1.08	336.1108	IT14
11.	2	14.9	14.377	1.08	484.2588	IT15

Fig: 19. Effect of Shell Wall Thickness on Tolerance Grade w.r.t Curve Radius

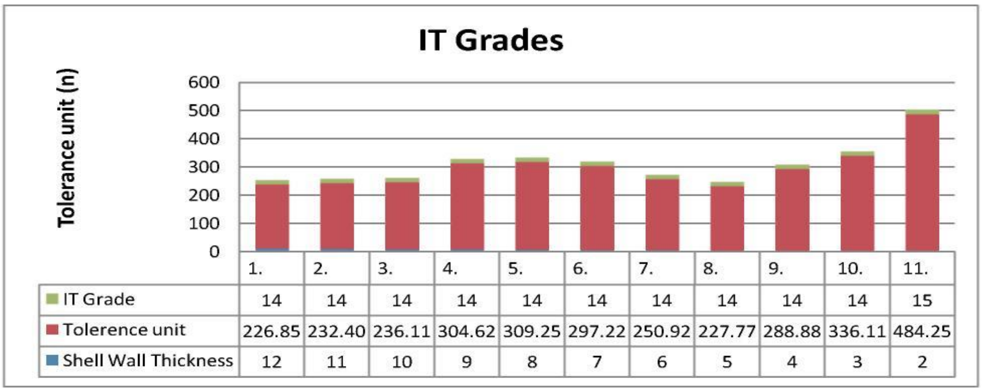


Table: 8. Class of Different IT Grade w.r.t. Outer Diameter for Lead Alloy

Experiment Number	Shell Wall Thickness (mm)	Outer Diameter as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		DJN	DJM			
1	12	50	49.2648	1.58	465.3165	IT14
2	11	50	49.2980	1.58	444.3038	IT14
3	10	50	49.3313	1.58	423.2279	IT14
4	9	50	49.3451	1.58	414.4937	IT14
5	8	50	49.1598	1.58	531.7722	IT14
6	7	50	49.2679	1.58	463.3544	IT14
7	6	50	49.3816	1.58	391.3924	IT14
8	5	50	49.2885	1.58	450.3165	IT14
9	4	50	49.2768	1.58	457.7215	IT14
10	3	50	48.5745	1.58	902.2152	IT15
11	2	50	48.5545	1.58	914.8734	IT15

Fig: 20. Effect of Shell Wall Thickness on Tolerance Grade w.r.t. Outer Radius

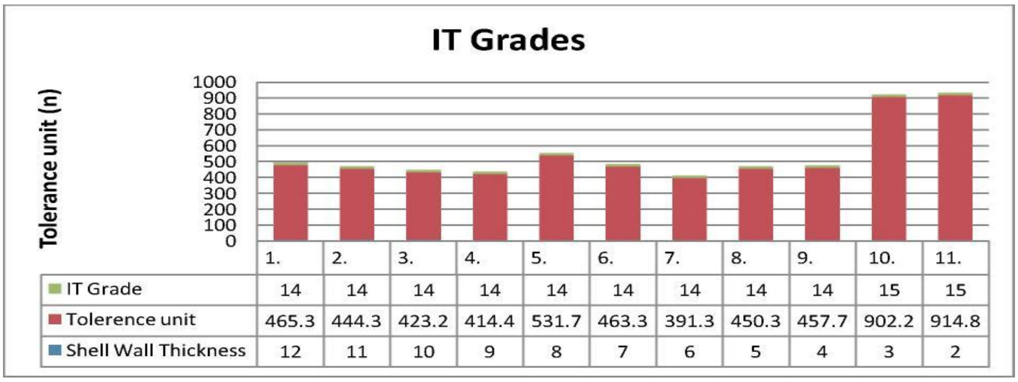
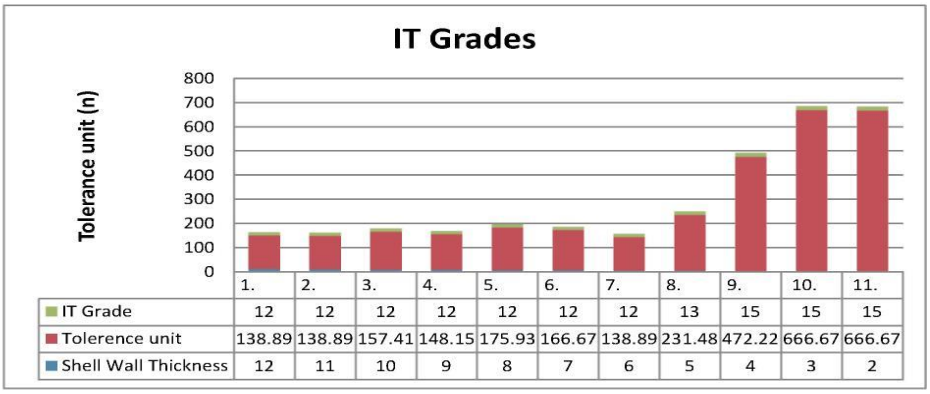


Table: 9. Class of Different IT Grade w.r.t. Outer Diameter for Lead Alloy

Experiment Number	Shell Wall Thickness (mm)	Curve Radius as Dimension of Component (mm)		Standard Tolerance Factor (i)	Tolerance unit (n)	IT Grade
		DJN	DJM			
1.	12	14.9	14.75	1.08	138.8888	IT12
2.	11	14.9	14.75	1.08	138.8888	IT12
3.	10	14.9	14.73	1.08	157.4073	IT12
4.	9	14.9	14.74	1.08	148.148	IT12
5.	8	14.9	14.71	1.08	175.9258	IT12
6.	7	14.9	14.72	1.08	166.6665	IT12
7.	6	14.9	**14.75**	1.08	138.8888	IT12
8.	5	14.9	14.65	1.08	231.4813	IT13
9.	4	14.9	14.39	1.08	472.2218	IT15
10.	3	14.9	14.18	1.08	666.666	IT15
11.	2	14.9	14.18	1.08	666.666	IT15

Fig: 21. Effect of Shell Wall Thickness on Tolerance Grade w.r.t Curve Radius



5.0 Results and Discussion

1. From figure 4, 8 and 11, and figure 5, 9 and 12, it has been observed that the dimensional accuracy increases with decrease in shell thickness from the recommended 12 mm to 5mm in case of aluminium, 5mm for zinc and 6 mm for lead and further it start decreasing with a decrease in shell thickness. This may be due to the change in the rate of heat transfer. According to Fourier law, the rate of heat transfer is given by Q= KA dT/dX . In the present casting method, the temperature difference (dT), dX (sum of shell and sand thickness) and Area of heat transfer remains constant. Only the thermal conductivity K effect the heat transfer, which may be better for 5mm, 5mm and 6 mm shell wall thickness in case of aluminium, zinc and lead respectively in present environmental conditions.

For aluminium alloy

The dimensional error for 12mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.1868)/50 = 1.626%

The dimensional error for 5 mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.1871)/50 = 1.625% The improvement in dimensions = 1.6264 - 1.625 = 0.0014%

For zinc alloy

The dimensional error for 12mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.2774)/50 = 0.01445x100 =

1.445% The dimensional error for 5 mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.3131)/50 = 0.013738 = 1.3738% The improvement in dimensions

= 1.445- 1.3738 = 0.0712%

For lead alloy

The dimensional error for 12mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.2648)/50 = 0.0147x100 = 1.47% The dimensional error for 5 mm shell thickness was calculated as

= $(D_{JN}- D_{JM})/D_{JN}$ = (50-49.3816)/50 = 0.012368 = 1.2368% The improvement in dimensions = 1.47- 1.2368 = 0.2332%

2. From figure 6, 10 and 13, it has been observed that the better hardness results were observed at 5mm, 5mm and 6 mm shell wall thickness in the case of aluminium, zinc and lead respectively.

3. Table 4 and 5 shows the Class of different IT Grade w.r.t. Outer Diameter and curve radius for aluminium, Table 6 and 7 shows the Class of different IT Grade w.r.t. Outer Diameter and curve redius for zinc and Table 8 and 9 shows the Class of different IT Grade w.r.t. Outer Diameter and curve redius for lead. The tolerance grades of the castings produced from different thickness were consistent with in the permissible range of tolerance grades IT grades as per standard UNI EN 20286-I (1995).

4. Table 3 shows the observations of shell wall thickness for production cost and production time. The effect of shell wall thickness on production cost for shell mould is shown in figure 14 and effect of shell wall thickness on production time for shell mould is shown by figure 15.

Figure 16, 18 and 20 shows the effect of shell wall thickness on tolerance grade w.r.t. outer diameter where as Figure 17, 19 and 21shows the effect of shell wall thickness on tolerance grade w.r.t. curve radius.

6.0 Conclusion

The 3DP technique describes good results, limited at present to the field of light alloy materials. The results ensure much higher geometrical freedom and permit the overcoming of the traditional shape definition concept as compare to traditional sand casting. A dimensional characterization has been performed on the obtained technological prototypes, through measurements on a CMM compared with the relative nominal positions. The results of the tolerance grade have been evaluated. It was concluded and proved that the affectivity of rapid casting for the production of cast technological prototypes, in very short times by avoiding any tooling phase and with dimensional tolerances that are completely consistent with processes of metal casting. Based on the results of this critical analysis, an attention-grabbing development of the research could be the assessment of the tolerance class of other parts produced with this process, aiming at the construction of a database for the precision and repeatability of rapid casting solutions. On the basis of experimental observations made on the different light alloy castings obtained from different shell wall thickness, the following conclusions can be drawn:

1. New products for which the cost of production of dies and other tooling is more, this procedure is better idea to demonstrate its feasibilty.
2. It is feasible to reduce the shell thickness from the recommended value of 12 mm to 2 mm for generating Aluminium, Zinc and Lead castings using mould manufactured in 3DP by using ZCast501 powder on model Z 510 Z print machine. The tolerance grades of the castings produced from different thickness were consistent with in the permissible range of tolerance grades (IT grades) as per standard UNI EN 20286-I (1995).
3. The dimensional accuracy obtained with optimum shell wall thickness as compared to the recommended shell wall thickness. Instead of recommended 12 mm SWT of mould in ZCast process of light alloys casting like Aluminium, Zinc and Lead can be taken as 5 mm, 5 mm and 6 mm respectively.
4. The experimental results indicate that at the 5 mm, 5 mm and 6 mm shell wall thickness, hardness of the casting was improved by 4.08%, 3.57% and 12.5% respectively in comparison to 12 mm the recommended shell wall thickness.
5. The experimental results indicate that at the 5 mm, 5 mm and 6 mm shell wall thickness, the production cost was 54.28%, 54.28% and 49.12% less in comparison to 12 mm recommended shell wall thickness.
6. The experimental results indicate that at the 5 mm, 5 mm and 6 mm shell wall thickness, the production time was 46.05%, 46.28% and 43.42% less in comparison to 12 mm recommended shell wall thickness.
7. Knowledge of the influence of various process parameters on the quality of shells and subsequent castings is essential in effectively employing shell casting in real-world applications.

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