A Study for Analyzing Effects of Design Parameters in the Sand Casting Process of Aluminum Alloy

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Abstract: The use of aluminum alloys are of significant use in industry. Studying of design parameters of such products is important as not much work has been done for optimizing it. The generic formulation involves the flow, velocity, continuity fluid dynamics and shape related issues. The time for filling the mould and shape factor also play major role in performance of the casting process. In this paper, a simple shape is chosen, designed and mould is finalized. From casting and then design experiments with the stated parameters, an optimized design values have been obtained. The effects of each design parameter aid us to identify and prioritize them for improvement of the process. This give first rough cut estimate of the variables in sand casting process.

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Introduction:

This paper is about experimental study of design parameters of Al alloys using casting processes. Casting processes by using aluminum alloy is of great significance in industry [1]. In sand casting process, metal is being melted and pouring into a preformed cavity called mold [2] and expandable molds are used in our case. Wood is a common pattern material because it is easily worked into shape [3]. These days pattern can be made in rapid and fast product manufacturing machines like Rapid Prototyping Machine [6]. In the typical mold for a sand casting there are set of channels through which a molten metal flows to the mold cavity is called gating system. Typical gating system consists of a pouring cup and a sprue receiving the poured melt, runner a channel through which the melt is supplied to the gates through which the molten metal enters the mold cavity. A gating system may include a riser a cavity connected to the gating system feeding the casting when it is shrinking. Air within the mold cavity and gases formed when a molten metal contacts the mold surface are removed through the vents. The interior cavities of a casting are formed by a separate inserts called cores. Cores are usually made of sand and backed [5]. A mold frame (flask) consists of two parts: cope (the upper part) and drag (the lower part). A mold cavity is formed in the process of pattern molding, when the pattern (commonly wooden) is embedded in sand in the flask forming an impression of the casting. After the sand packing the pattern is removed from the flask and the cores and the gating system are arranged. Cores, runner and gates are arranged in the drag; pouring cap and sprue are placed in the cope. Then the two parts of the mold are assembled and poured. After the metal has solidified and cooled to a desired temperature, the casting is removed from the mold by the process called shakeout [6]. The gating system (gates, sprues and risers) provides paths for the molten metal to flow into the mold as given in Figure 1.

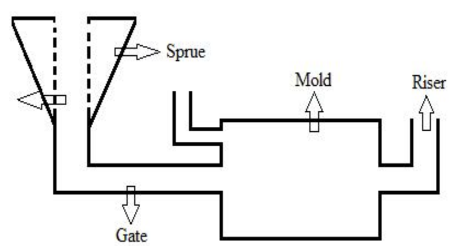

Figure 1 Basics components of casting system

Gates have to promote high volume, low velocity flow. Gating system consists of gate is the end of the runner in a mold where molten metal enters the mold cavity and consists of top and bottom gates. Also consists of Sprue is the vertical channel from the top of the mold to the gating and riser system. Also, a generic term used to cover all gates, runners and risers. Be formed straight, cylindrical and tapered. Also consists of Riser is a reservoir of molten metal provided to compensate for the contraction of the metal as it solidifies. There are single or more than two risers at the center [6,7]. The provision of a sprue base well at the bottom of the sprue helps in reducing the velocity of the incoming metal and also the mould erosion. A general guide line could be that the sprue base well area should be five times that of the sprue choke area and the well depth should be approximately equal to that of the runner [6].

The function of a riser is to feed the casting during solidification so that no shrinkage cavities are formed. The requirement of risers depends to a great extent upon the type of metal poured and the complexity of the casting. The mathematical analysis has been collected from [5, 6, 7]. The casting experiment is performed and we measured the data i.e. gate diameter, height of mould, height of material, height of the mould box, pattern surface area and volume (from Solidworks™ software), length and diameter of sprue and riser positioning details etc. After discussion and studying literature, we concluded to analyze the following: a) The gates (bottom or upper gate); b) Sprue analysis (whether to put it straight or parabolic); c) Riser details (only positioning)

With this information, we describe the mathematical model and then use data to calculate and analyze. The analytical model related to the gating systems, sprue and risers influence the casting performance. It is necessary to analyze the casting using relationships, which has been discussed in literature [1] [2]. The bottom gate configuration is shown in figure 2.

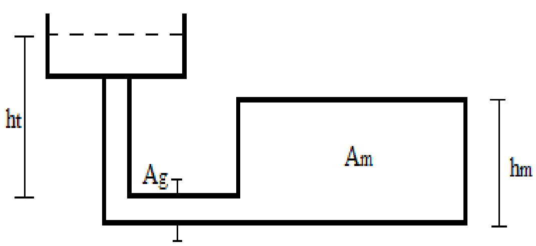

Fig.2: Bottom Gate

The parameters for the bottom gate casting process are A_g=in-gate area, A_m = cross-sectional area of casting, h_t= filling height, A_s is gate area and h_m is height of casting. The relationship for the bottom gate casting process is

$$t_p = \frac{2\,A_m}{A_g\sqrt{2g}}\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)$$

For the top gate casting process, the relation is

$$\text{Filling time for the mold} = \frac{\text{Volume of mold}}{\text{Gate area} \times \text{Velocity}}$$

$$t_p = \frac{A_m\,h_m}{A_s\,V_g}$$

To ensure that liquids melt is clean and degassed. Atmospheric gases can be introduced to the metal through aspiration. Aspiration occurs when pressure anywhere in the liquid falls below atmospheric pressure which most often in the vertical sprue [6]. The often condition is when sprue is tapered. The taper is required to avoid aspiration as shown in figure 3 can be calculated using Bernoulli's equation. The final equation is

$$\frac{A_2}{A_3} = \sqrt{\frac{h_c}{h_t}}$$

This equation provides an estimate of the maximum taper ratio required to prevent aspiration. If Bernoulli's equation is applied along the whole length of sprue parabolic shaped riser is generated.

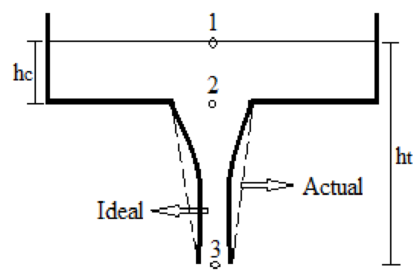

Fig.3: Geometry of Sprue for Casting [6]

The above equation can be modified as

$$d = \sqrt{d_1^2\sqrt{\frac{h_1}{h}}}$$

$$d = c\,h^{-0.25}$$

Development of Parts and Experimentation:

A split wooden or metal master pattern is made of the shape to be cast. One half of the pattern is positioned on a bottom board and surrounded by the drag flask (bottom) half of the molding. A parting compound, such as talc, is sprinkled over the pattern to facilitate separation of the pattern from the mould prior to pouring the liquid metal. It must be sufficiently strong to hold the mould shape. Often fine sand is placed against the pattern and then a coarser sand mixture is used to fill the rest of the drag. Fine sand provides a relatively good surface finish on the cast part. The sand is packed tightly to ensure that the shape of the pattern is retained and excess sand removed. The drag is inverted and the top half, or cope, of the mould prepared in the same manner as the drag. A feeding system for delivery of the molten metal is formed in the cope. This typically consists of a pouring basin, a sprue (vertical metal transfer channel), runners (horizontal transfer channels) and in gates connecting the runners to the mould cavity. The feeding system can be made part of the pattern or can be carved into the split mould after the pattern has been removed. In addition to the feeding system, riser cavities are designed into strategic positions.

These serve as reservoirs of molten metal which are fed into the casting as it cools to compensate for solidification shrinkage. The cope and drag are separated and the pattern removed. A core of sand mixed with resin or ceramic is placed in the mould to form the hollow of the pipe. The strength of the core must be higher than the rest of the mould to prevent damage from the inrush of molten metal. The cope and drag are reassembled and clamped together, ready for receipt of the metal. The metal is poured from a small ladle into the sprue, flows into the mould cavity and solidifies. Once solidification is complete the mould is broken and the cast part removed, all sand cleaned off and the riser and feeding system are cut away. To sand cast complex shapes, the sand must be sufficiently strong to hold the mould shape.

One of the most common casting processes specified is Sand Casting [6]. This process is divided into two different methods, typically chosen by the foundry based upon size, quantity and alloy being cast. The two methods rely upon the same type of tooling (called patterns and core boxes), but utilize different sand systems. The size of castings produced in sand molds spans the full range of casting weights from ounces to tons. Low volume castings are typically produced by hand, with low pressure molding of the sand. The gating system that allows the molten metal to fill the mold can either be part of the pattern (preferably) or cut into the sand manually. By Software Solid Work, we can draw the next shape which is the pattern before the casting processes as shown in figures 4 below.

After making the mould, we have the advantage of better dimensional tolerances and improved surface finish. Although the sand casting of simple shapes. We got three different shapes before and after the sand casting processes are pattern, top and bottom gates. By Software Solid Work, we can draw the previous shapes as shown in figures 5 and 6 respectively.

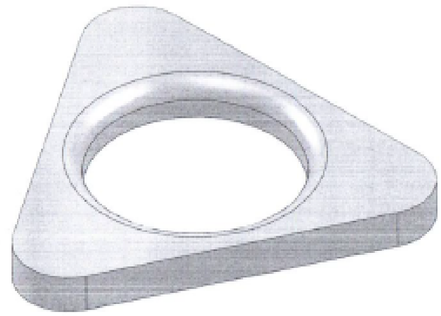

Fig.4: The Pattern used

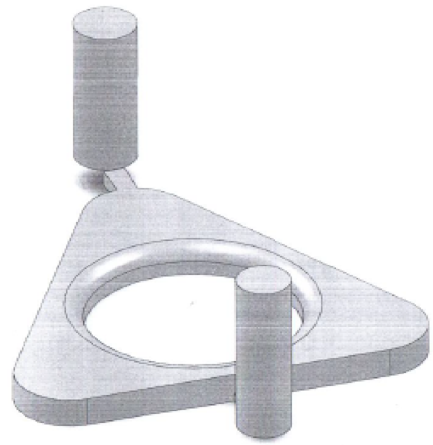

Figure 5 Bottom gate

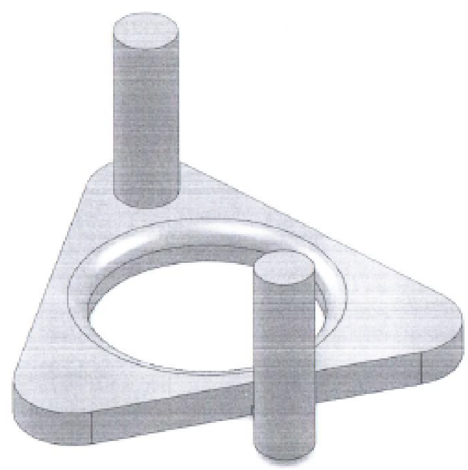

Figure6: The Top Gate

Parameter Details and Analysis:

During the experiment procedures, we took data (measured and calculated) and given dimensions after measured from experiment in Table.1.

Table 1: Data & Given Dimensions

Diameter of ingate for bottom gate	17.55 mm
Diameter of ingate for top gate	24.5 mm
Filling height, h_t	50 mm
Height of casting, h_m	50 mm
Diameter of sprue (Large)	29 mm
Diameter of sprue (Small)	12 mm
Height of sprue, h	51 mm
Height of riser, h	17 mm
Height of sprue, h_c	49.5 mm
Diameter of riser	25.5 mm
Height of riser, h	36.5 mm
Thickness of riser, t	16.5 mm

By Software Solid Work, we can calculate A_m (Surface area) & volume of mold,

$A_m =$ 15080.38 mm^2, Volume = 49192.41 mm^3

- At bottom gate:

Diameter for $A_g = 17.55$ mm

$$A_g = \frac{\pi}{4} d^2 = \frac{\pi}{4}(17.5)^2, \quad A_g = 241 \text{ mm}^2$$

$$t_p = \frac{\text{Area of mold}}{\text{Gate area}} \frac{1}{\sqrt{2g}} 2\left(\sqrt{\text{static head}} - \sqrt{\text{static head}} - \sqrt{\text{height modal}}\right)$$

$$t_p = \frac{2\,A_m}{A_g\sqrt{2g}}\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)$$

$$t_p = \frac{2 * 15080.38}{241\sqrt{2 * 9810}}\left(\sqrt{53.5} - \sqrt{53.5 - 50}\right)$$

$$t_p = 4.86 \text{ s}$$

- At top gate

Diameter for $A_g = 24.5$ mm

$$A_g = \frac{\pi}{4} d^2 = \frac{\pi}{4}(24.5)^2, \quad A_s = 471.4 \text{ mm}^2$$

$$h_m = 50 \text{ mm}, \quad h_t = 50 \text{ mm}$$

$$A_m = 15080.38 \text{ mm}^2, \quad g = 9810 \text{ mm / s}^2$$

$$V_g = \sqrt{2\,g\,h_t} = \sqrt{2 \times 9810 \times 50}$$

$$V_g = 990.45 \text{ mm}^3$$

$$t_p = \frac{A_m\,h_m}{A_s\,V_g} = \frac{15080.38 \times 50}{471.4 \times 990.45}, \quad t_p = 1.6 \text{ s}$$

The time for the top gate is less, but the material will be more turbulent. We are studying the flow effects [6], we leave this part and suggested design is the bottom gate and further analysis is done on it.

The parabolic type of sprue is recommended in most cases as it avoids the aspiration formed during casting process. This is given below:

We have,

Diameter of sprue = 29 mm

$$A_{sprue} = \frac{\pi}{4}(29)^2$$

$$A_{sprue} = 661 \text{ mm}^2$$

$$\text{Volume of sprue} = A_{sprue}\,h$$

$$Vol_{sprue} = 661 \times 51 = 33711 \text{ mm}^3$$

$$h_c = 49.5 \text{ mm},$$

$$h_t = h_c + h$$

$$h_t = 49.5 + 17 = 66.5 \text{ mm}$$

It is appropriate to apply boundary conditions in order to design the parabolic sprue according to the details. We have boundary conditions as shown in figure 7.

1) At $h = h_o$, d = 29 mm
2) At $h = h_o + 51$ mm , d = 12 mm

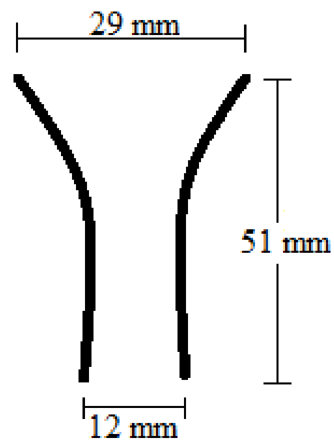

Fig.7: Boundary condition 1 & 2

At boundary condition 1:

$d = c\,h^{-0.25}$

$29 = c\,h^{-0.25}$

$c = 4\,h_0^{-0.25}$

At boundary condition 2:
$12 = c\,(h_0 + 51)^{-0.25}$
$12 = (4\,h_0^{0.25})(h_0 + 51)^{-0.25}$
$h_o = 831.02$ mm
$c = 21.4$

So, required equation is

$d = c\,h^{-0.25}$
$d = 21.4\,(831.02 + 51)^{-0.25}$
$d = 0.39$ mm, this is optimal diameter with minimum aspiration or air trapped.

The riser is the last part in the casting process which solidifies in the end. This also play major part in casting to avoid the casting defects during pouring and when material will come out from the riser. For big castings, more than one riser is needed, but in our case we follow the practice of actual casters (based on judgment). However, an analysis is given which will aid the designers in positioning and selecting the riser.
We, have

Diameter of riser = 25.5 mm

$$A_{riser} = \frac{\pi}{4}(25.5)^2$$

$$A_{riser} = 511\ mm^2$$

Volume of riser = $511 \times 51 = 26061\ mm^3$

h = height of metal in the mold = 17 mm

$h_t = 36.5 + 17 = 53.5$ mm, $h_m = 50$ mm

Riser position and location are shown in figure 8

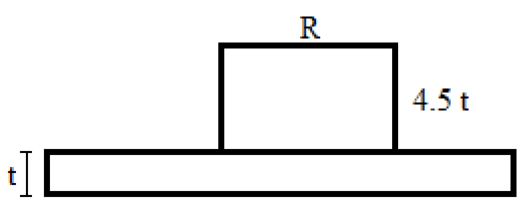

Fig 8: Riser position and location

t = thickness = 16.5 mm

Location of the riser is also shown in figure 9.
$4.5 \times 16.5 = 74.25$ mm

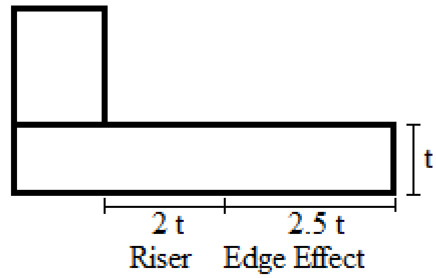

Fig.9: Riser Edge Effect

This mean, single riser is enough if feeding length is less than 4.5 times plate thickness. Sprue length single riser = 51 mm < 4.5 t.

Results and Discussion:
Experiments (DOE) techniques enable designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements; therefore, it helps turn any standard design into a robust one. Simply put, DOE helps to pin point the sensitive parts and sensitive areas in designs that cause problems in Yield. Designers are then able to fix these problems and produce robust and higher yield designs prior going into production [8].
For the formula of t_p for bottom gate, the DOE (Design of Experiments) is performed as it significantly affects the process and has following steps:
1. Start by choosing variables that affect the response, the inputs are (nominal values)
Ag : Diameter of gate = 241 mm^2 (calculated from experiment)
h_t : Filling height = 53.5 mm (measured from experiment)
h_m : Casting height = 50 mm (measured from experiment)

2. Run the simulation eight times to get the gain (our output measure) for all the combination of +1's and -1's of the three elements and this is what we get
There are 3 variables, so there will be $2^3 = 8$ effects to be analyzed. Here, we will make changes in full factorial design,
For a value of d = 241mm^2,
-1 correspond to 236 mm^2
+1 correspond to 246 mm^2
0 correspond to d = 241 mm^2
3. Make main effects table and take averages of -1 and 1 and then calculate slope. The main effects are given below:
a) Main effect of h_m on t_p in Table 2 as following:

Table 2: Main Effect of h_m on t_p

d	h_t	h_m	t_p
-1	-1	-1	14.45
1	-1	-1	13.87
-1	1	-1	11.30
1	1	-1	10.81
-1	-1	1	12.55
1	-1	1	12.04
-1	1	1	15.40
1	1	1	15.15

- Average t_p for h_m = -1 = $\frac{14.45+13.87+11.30+10.81}{4}$ = 12.607 s
- Average t_p for h_m = 1 = $\frac{12.55+12.04+15.40+15.15}{4}$ = 13.785 s
- The slope = 13.785 - 12.607 = $\frac{1.178}{2}$ = 0.58875

The graph of main effect of h_m on t_p as shown in figure 10

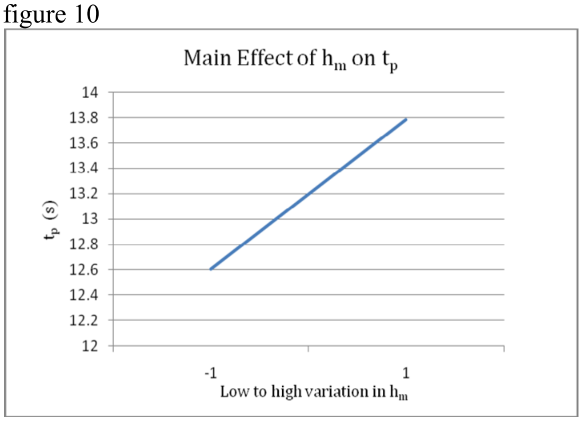

Fig.10: Main effect of h_m on t_p

b) Main effect of h_t on t_p is

- Average of t_p for h_t = -1= 13.227
- Average of t_p for h_t = 1 = 13.165
- The Slope = 0.031

The graph of main effect of h_t on t_p in figure 11 as following:

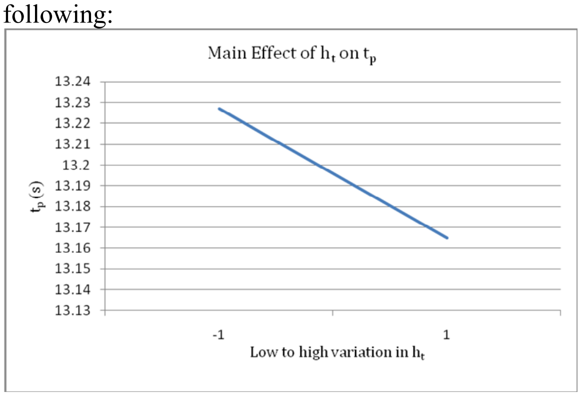

Fig.11: Main effect of h_t on t_p

c) Main effect of d on t_p is

- Average tp for d = -1= 13.425
- Average tp for d = 1 = 12.967
- The Slope = 0.229

The graph of main effect of d on t_p in figure 12

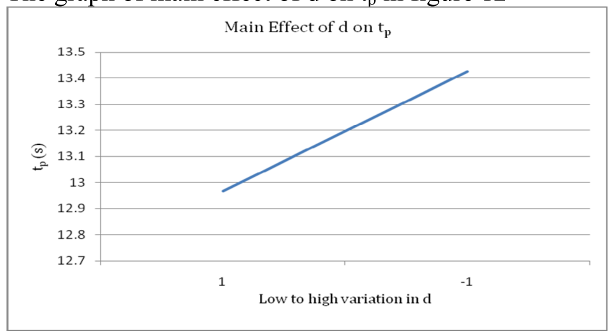

Fig.12: Main effect of d on t_p

d) Interaction Effect of d and h_t is

- Average tp for d = -1= 13.152
- Average tp for d = 1 = 13.24
- The Slope = 0.043

The graph of interaction effect of d and h_t on t_p in figure 13

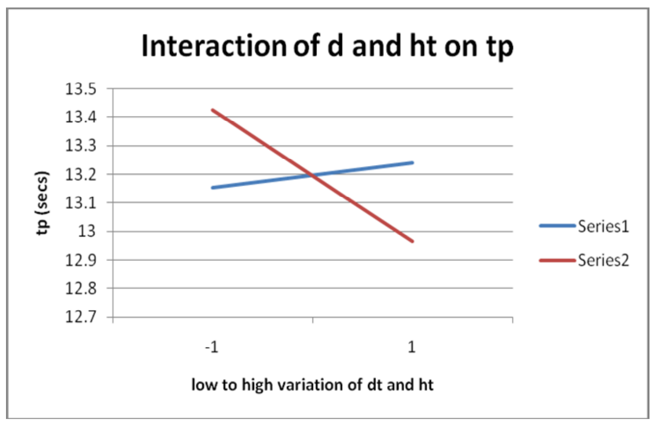

Fig.13: Interaction effect of d and h_t on t_p

e) Interaction Effect of d and h_m on t_p is

- Average tp for d = -1= 13.157
- Average tp for d = 1 = 13.235
- The Slope = 0.039

The graph of interaction effect of d and h_m on t_p in figure 14

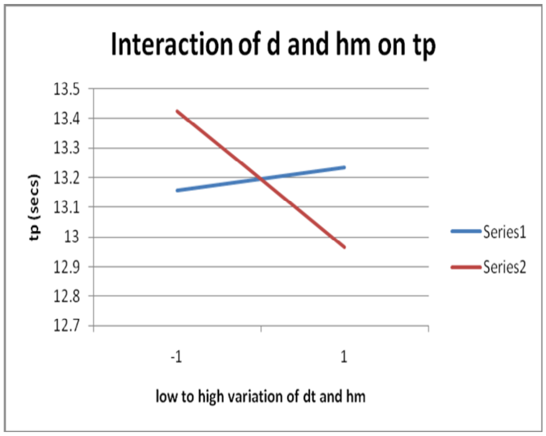

Fig.14: Interaction effect of d and h_m on t_p

f) Interaction Effect of ht and h_m on t_p is

- Average tp for d = -1= 14.717
- Average tp for d = 1 = 11.675
- The Slope = 1.521

The graph of Interaction Effect of ht and h_m on t_p in figure 15 as following:

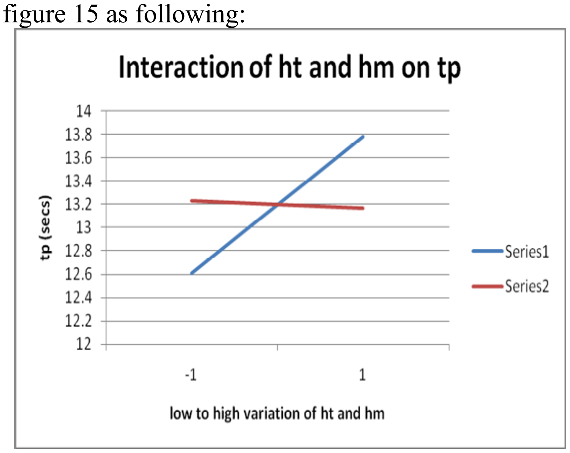

Fig.15: Interaction Effect of ht and h_m on t_p

Interaction effect of h_t and h_m on t_p is

- Average tp for d = -1= 13.175
- Average tp for d = 1 = 13.217
- The Slope = 0.0212

The graph of Interaction Effect of ht and h_m on t_p in figure 16

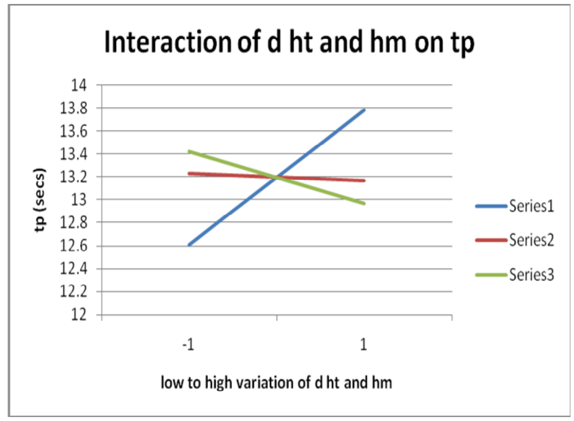

Fig16: Interaction effect of ht and h_m on t_p

The bove stated results, it is experimentally proved that the main factors effecting are the interaction of ht and hm, then hm and d. The ht and hm are the casting design related. We have analyzed for d and suggested the improved design of 'd', which has already been tested for different casting figures. Now, we have terms & coeffcients in Table 3 as follows

Table 3: Terms & Coefficients

Terms	**Coefficients**
Constants	15.15
h_m	0.58875
h_t	0.031
d	0.229
d and h_t	0.043
d and h_m	0.039
h_t and h_m	1.521
d h_t and h_m	0.0212

The final govering equation covering all of the parameters is

$$t_p = 15.15 + 0.58875h_m + 0.031h_t + 0.229d + 0.043d * h_t + 0.039d * h_m + 1.521h_t * h_m + 0.021d * h_t * h_m$$

Contribution of all variables on the t_p is shown in Pareto chart in figure 17 as follows:

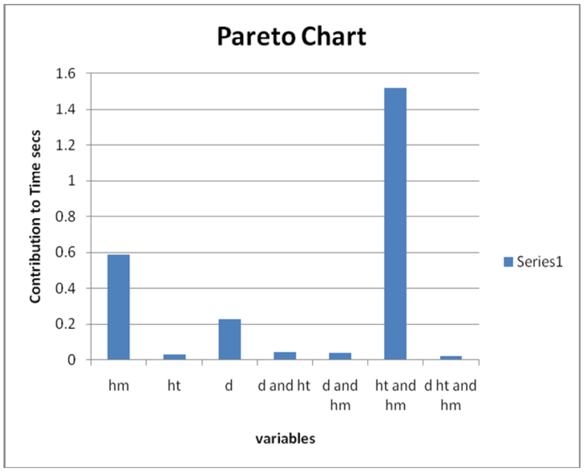

Fig.17: Prioritized results using Pareto chart

Conclusion and Recommendations:

The sand casting process performed in the workshop has steps. The pattern has been made in Solidworks^{TM} and separate experiments performed using bottom and top gate. Pattern is made in Solid works software and volume and surface area calculated there. Using standard mathematical routines, the experiment details are coded and calculations performed.

Three types of calculations performed are gates (bottom or top), sprue geometry effecting the design and number of risers needed. It was shown that the bottom gate is better as it avoid casting defects reducing effects of turbulent flow (not studied), but it is experimentally found to be best solution for casting using bottom gate. The sprue geometry of the parabolic best fit and mathematically solved for our case of figure and reduces aspiration. The last is the number of risers needed for such analysis. It is only one riser needed for such part.

Then DOE (Design of Experiment) was done to see the most contributing factors in casting design. The time for the bottom casting process is selected as this the major technique used in industry [6]. The number of variables in this routine is three and list of experiments performed are eight. The procedure is described in previous chapters and it is found that the interaction of ht and h_m is the most contributing in the overall design of the casting. This means that the designer has to focus on the geometrical details of the casting process. This is followed by h_m which is second contributing factor. The sprue diameter design 'd' are third contributing factors in our case. This'd' is further used to design the casting diameter for our case and it helped to reduce the defects. A mathematical model has been developed for the case specific model of the casting and in this process, contributing factors have been highlighted. The Pareto chart is used to analyze the process which can help to understand the significance of various factors in given scenario. It is recommended that for the sand casting of aluminum, focus should be on the mould, mould temperature, furnace temperature, temperature of the aluminum outside the furnace, using flux like $CaCO_2$ in order to remove the thick cream on the aluminum. Use of parabolic sprue design is recommended in any casting type and number of risers depending upon the type of casting. The bottom gate is better option which improves the life of casted parts.

The future work include using die casting as available in our workshop, use of some other design of experimental method and comparing with this to improve process.

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References

1. Jacob S.; The quality index in the prediction of properties of aluminum castings: a review, Hommes&Fonderie, December 2001, Nr. 319
2. M. C. Flemings, Solidification Processing, McGraw-Hill Inc., London,1974.
3. W. Kurz, D. J. Fisher, Fundamentals of solidification, 4th Rev. Ed.,Trans Tech Pub., Switzerland, 1998.
4. Mohd Rizwan Mohammed Shafieei, Mohd Yussni Bin Hashimii and Mohd Nusyakirin Bin Saidiii, Effects of gating design on the mechanical strength of thin section castings, Proceedings of MUCEET2009, Malaysian Technical Universities Conference on Engineering and Technology,June 20-22, 2009, MS Garden,Kuantan, Pahang, Malaysia.
5. O. BOUSKA, the effect of different casting parameters on the relationship between flowability, mould filling capacity and cooling conditions of al-Si alloys, Association of Metallurgical Engineers of Serbia, METALURGIJA - JOURNAL OF METALLURGY, 2008.
6. Serope Kalpakjian, Steven R Schmid, Manufacturing Processes for Engineering Materials, Fitth Edition, 2008, Pearson Education, Prentice hall, USA.
7. Mikell P Groover, Manufacturing Processes, John Wiley & Sons, 2011.
8. Douglas C. Montgomery, Design and Analysis of Experiments, John Wiley 7th Edition, 2008.

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