CONTINUOUS IMPROVEMENT OF QUALITY AT DIE CASTING PLANT

[1]Nikhil Nandha V, [2]Dr. Shobha N S

[1]Student, [2]Assistant Professor
[1]Industrial Engineering and Management,
[1]R.V College of Engineering, Bangalore, India

Abstract: The main purpose of this work is to analyze and determine the type of defects occurring in the die casting process. In any die casting process, porosity is a very serious problem faced by the Production Planning Committee and also being an impregnable defect, it is not identified visually through naked eyes. Porosity formation limits the use of die-cast parts in applications which requires high strength. Porosity rejections account for 40% of the total rejections. To analyze the causes and remedies relating to the defects and to reduce the porosity formation Design of Experiments (DoE) is carried out. Quality tools such as fishbone or Ishikawa diagrams and pareto charts were used to analyze and scrutinize the causes for the defects. The optimal setting of the parameters and the subsequent effect of the selected parameters on the porosity formation was accomplished using Taguchi method. The final results indicated that the critical parameters selected considerably affected the porosity formation in aluminium alloy die castings. Design of Experiments (DoE) was performed with the use of Minitab software. The optimal setting of parameters was found at level 2 of all the factors. The predicted value of density for the optimal setting of parameters was found to be 2.62169 g/cm³ and when compared to its standard value, the porosity percentage was reduced to 2.9% from almost 4%.

Key words **- High pressure die casting, Design of Experiments, Taguchi method**

I. INTRODUCTION

Today, automotive suppliers are very concerned about quality improvement as well as improved system productivity. To stay competitive, waste from the system must be identified and removed in order to run the system more efficiently. Foundry businesses are growing and have a significant influence on the automobile industry's competitiveness. Die casting is one of the most established and developing procedure in the worldwide economy. It follows the rule of perpetual form projecting cycle (permanent mould casting process), where exterior pressure is utilized to top off the shape. The Pressure is kept up during the hardening process to deliver impenetrable castings. This pressure is called the intensification pressure. The HPDC process is utilized to deliver parts made of different non-ferrous metals like Brass, Zinc, Aluminum, and Magnesium. It can deliver intricate shapes. The various kinds of die casting technologies are pressure die casting, gravity die casting, and vacuum die casting. Die casting procedures have gotten more complicated, resulting in faults. One of the most recurring flaws found in aluminium die castings is porosity. Porosity development results in high-cost scrap and restricts the use of die-cast components in high-strength applications. Die casting process factors have a strong influence on the degree of porosity in a product. To reduce production errors, the die-cast design and specifications must be flawless. The goal of this project is to thoroughly examine the process and determine the optimal level of parameters. The high pressure die casting method will be discussed here. The Design of Experiments is the process of planning experiments by collecting appropriate data, performing the minimum number of experiments to obtain necessary technical information, and using suitable statistical methods to analyze the collected data. DoE is used to investigate the effects of variables and the hidden causes for the process variation. This improves a product's manufacturability, reliability, and quality.

II. Literature Review

Though various strategies have various impacts, Logothetis [1] specifies that discover a plan that is solid and beneficial to variations. Pradip Gunaki and S.N. Teli [2] exhibits a process flow diagram that mirrors the present status of the activities. The NVA activities are distinguished in each operation by the futile time and resources. This paper illuminates the remedial activities for wiping out the NVA activities in the die casting unit with the assistance of Arena simulation software. Javedhusen Malek and Darshak Desai [3] concentrated on giving a way to Indian SME's for starting the Six Sigma approach in their businesses. They talked about the genuine case at one of the Indian MSME units where Six Sigma was effectively carried out to further develop dismissal/improve rate where items were produced by PDC process. They likewise portrayed exhaustively pretty much every one of the stages that were utilized in this examination which incorporated every one of the areas of define, measure, analyse, improve, and control (DMAIC) which showed effect of Six Sigma in quality improvement. Avinash [4] carried out an industrial contextual investigation to lessen projecting imperfections. The primary instrument utilized was the ishikawa diagram or fishbone outline, as it helps in deciding the critical parameters that are generally persuasive on the quality of casting.

Later in the 1950s, Dr. Genichi Taguchi presented a few new factual instruments and ideas of quality improvement that rely intensely upon the hypothesis for DoE. Dean [5] recommended that the Taguchi method can have advantages like time and capital thrift, identification of significant control factors, and reduced over heads and execution that creates high quality result.
Taguchi presents his methodology utilizing test plan for:
(a) Planning processes that are healthy to environmental situations.
(b) Scheming procedures that are sturdy to component variation.
(c) Reducing the dissimilarity around a certain specific value.

Dr. Taguchi contemplates three phases in the process advancement:
(a) framework plan
(b) boundary plan
(c) resistance plan

K S Anastasiou [6] accepts that an impressive decrease in porosity development can be accomplished by carrying out the Taguchi strategy in the PDC process. Porosity on castings have consistently been an issue and, despite notable examination, R&D, the expanding intricacy of castings requested by industry has made it basically difficult to take out porosity by and large, however boundary enhancement of the critical factors can limit the porosity occurrence to non-critical areas. He additionally carried out a projecting deformity examination utilizing the fishbone illustration to investigate the factors that influenced the molding quality. The critical factors were split into four principal classifications linking to: the die casting machine, shot sleeve, mold or die, and nature of casting alloy. From these set of factors, molten metal temperature, mold temperature, piston velocity (first and second) and hydraulic pressure were considered as the main reasons influencing the quality. Kulkarni Sanjay Kumar [7] considered the impact of various settings on the porosity levels. The factors were like the past approach, yet the lone contrast is the length at which the first stage velocity ends was considered as a significant factor.

In the 'Optimization of green sand-casting process by using method Taguchi's method' [8], Guharaja carried out DOE on a sand-casting process, where nine factors were chosen. The OA was chosen by computing the Degree of Freedom (DOF), which is given as 26 = [9 × [3-1] + 2 [×2]], where nine boundaries each at three levels and two interactions were utilized in the investigation. So, a L27 three OA was chosen. In another exploration led by Mahesh [9], a L9 OA was selected as there were four factors at three levels. Thus, the DoF is a vital characteristic in selecting the OA. Verran [10] carried out DoE examination on an aluminum compound that had a high number of dismissals because of porosity issues. DOE was performed and ANOVA was led at 95% of certainty. As a result, the quick shot and upset pressing factor and also their interactions were found to be the critical characteristics for the specified rejection reason. Kumar [11] performed die casting process improvement DoE utilizing the Taguchi method and ANOVA examination in Minitab package to decide the elementary factors that influenced porosity. The factual examination derived that the injection pressure and molten metal temperature were the critical and significant factors that influenced the porosity issue.

III. RESEARCH METHODOLOGY

This section provides the information about the methodology carried out in the project. It also contains the detailed information about the critical process parameters that affect the quality during the production process.

3.1 Process parameters and its significance

Almost every casting is a result of the process parameters that is set at the time of production. So, process parameters play an important role in the reduction of defects. Optimizing the process parameters will reduce the number of defects occurring up to a certain extend. The important parameters used and its significance are listed below.

3.1.1 Pouring temperature

Pouring temperature otherwise called liquid metal temperature usually shifts from 650 to 800 degrees Celsius. The aluminum compound shows up as ingots and it is melted in the furnace present near the die casting machine. Its smoothness into the mold is totally subject to the liquid metal temperature. The consistency and surface strain of liquid metal declines as the pouring temperature increments, so better smoothness can be accomplished which prompts the increased filling speed. The liquid metal temperature additionally influences the microstructure at a more noteworthy degree and which thus influences the final structure and durability of the projecting item. So, the pouring temperature is a basic factor to be thought of while a component is produced using HPDC measure.

3.1.2 Preheat temperature

Preheating is a process of warming up the mold before the production starts. Preheating in the die casting is done to eliminate the chance of occurrence of temperature gradients. On the off chance that the temperature of the die is incremented from a specific range, it might influence the die coat and create deformities like coarse surface appearance. On the off chance that the temperature is extensively low, then this may cause a cooling impact which prompts hardening issues in the center, and because of this distinction in cooling rate, issues like hardening, shrinkage porosity may occur. So, maintaining an ideal temperature of the mold surface is fundamental for the creation of top-notch castings.

3.1.3 Velocity of plunger

In a usual die casting process, a ladle is utilized to pour the liquid metal within the shot sleeve. During this cycle, the progression of the metal inside the shot sleeve ought to be in laminar. After the liquid metal is moved to the shot sleeve, the liquid metal is constrained into the shape of the mold by the movement of plunger (piston or cylinder) where it powers the liquid metal into the mold. Regularly, it is accomplished in two stages. The plunger moves at first with a low speed. Then, the speed increments during the cylinder's movement at the change-over position. The length moved by the piston up to change over point is known as first stage length and the infusion pressure is decreased towards the end when essentially all the fluid metal is infused into the mold. Then the molten metal hardens to form the desired shape. If the velocity, first stage length, and infusion pressure are not set as expected the flow of metal becomes turbulent. Thus, these factors increase the possibility of formation of porosity during process.

3.1.4 Nitrogen degassing

Aluminum Degassing is a filtration treatment that cleans the liquid metal by eliminating physical (hydrogen gas incorporations), and metallurgical (antacid salts) adulterations. In this technique, an inert gas (argon or nitrogen) is infused into the liquid metal through nozzles. The Aluminum Degassing Machine is set between the holding incinerator and the molding machine, and the inert gas blown into the liquid aluminum alloy is sliced by the spinning graphite rotor to produce a huge number of scattered air pockets (bubbles). The liquid aluminum alloy is adequately reached with nitrogen or Argon in the treatment tank. According to the pressure difference and surface adsorption principle, the air pocket absorbs hydrogen in the dissolve, and adsorbs the oxidized slag, and then ascends to the surface of the melt.

3.2 Steps for carrying out Design of Experiments

This section provides information about the methodology carried out. It also contains the detailed information about main root-causes for the defects, and critical parameters that affect the quality during the production process.

Figure 1. Procedure for conducting Design of Experiments

3.2.1 Identification of critical component and factors

Owing to confidentiality agreement, the name of the critical component cannot be revealed in the paper. The chosen component is manufactured in a four-cavity die using HPDC process. This component is responsible for securing the engine of a vehicle to the chassis and dampening the vibration. During its operation, the undesired vibrations generated by the engine will directly get transferred to the main frame. It may cause discomfort to the passenger or might damage the chassis. This component was selected after analysing the daily in-plant rejections for a period of 5 months. First the scrap rate for all the components along with their types were analysed from the month of January 2020 to May 2020. After which the components causing the greatest number of rejections was chosen. The table below depicts the number of rejections and the reasons for the rejections.

Table 1. Total rejection details for a period of 5 months

MONTH	REJECTION REASONS											TOTAL PRODUCTION
	NON-FILLING	SCORING MARK	PDC CRACK	RUNNER BREAKAGE	EJECTOR PROBLEM	LAMINATION	INCLUSION	POROSITY	BEND	DAMAGE	T.QTY	
JANUARY	1150	1866	489	142	0	12	80	4285	0	9	8033	633024
FEBRUARY	4348	6566	1045	346	21	0	47	9854	11	0	22238	667079
MARCH	5622	9386	645	521	44	1161	121	13767	476	960	32703	709549
APRIL	4192	3473	953	430	8	10	234	7799	199	0	17298	655158
MAY	2121	727	256	18	40	0	161	2861	38	200	6422	241728

The total percentage of rejections caused is about 2%. In the month of January out of 8,033 rejects rejections due to porosity contributes about 53% (4,285). As a total, out of 86,694 rejects rejections due to porosity contributes about 44% (38,566). It is evident from the table that porosity, scoring mark, and non-filling are the major issues. Here, the focus in the project would be to reduce the rejections that are caused due to porosity as it contributes the most. Figure 2 depicts the same in the form of pareto chart.

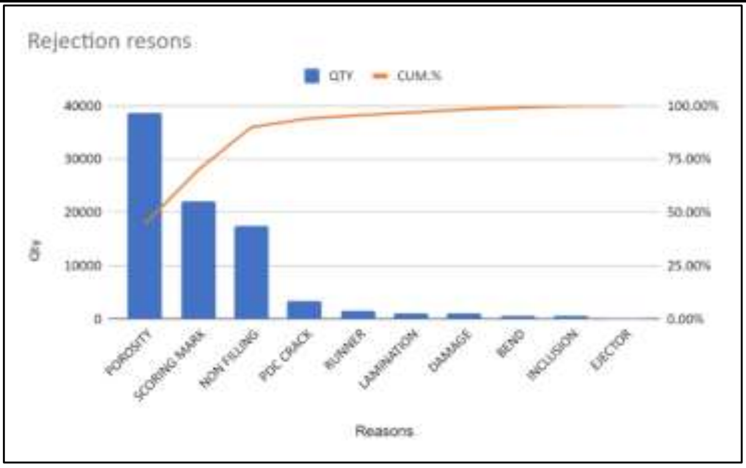

Figure 2. Pareto chart representing the types of rejection

After identifying the critical component, the causes which are related to the 4M's are identified so that the critical parameters for the rejection can be identified. To do this the fishbone or Ishikawa diagram is constructed with the 4M's which are basically Man, Machine, Material, and Method. After analysing the process and its parameters, it was found that the process parameters related to the method of manufacturing the component was the key reason behind the formation of porosity issue. The main process parameters that affected the component was the molten metal temperature, die temperature, plunger velocity phase1, and plunger velocity phase 2. Fig 3 shows the cause-and-effect diagram with all the major causes that leads to the formation of porosity.

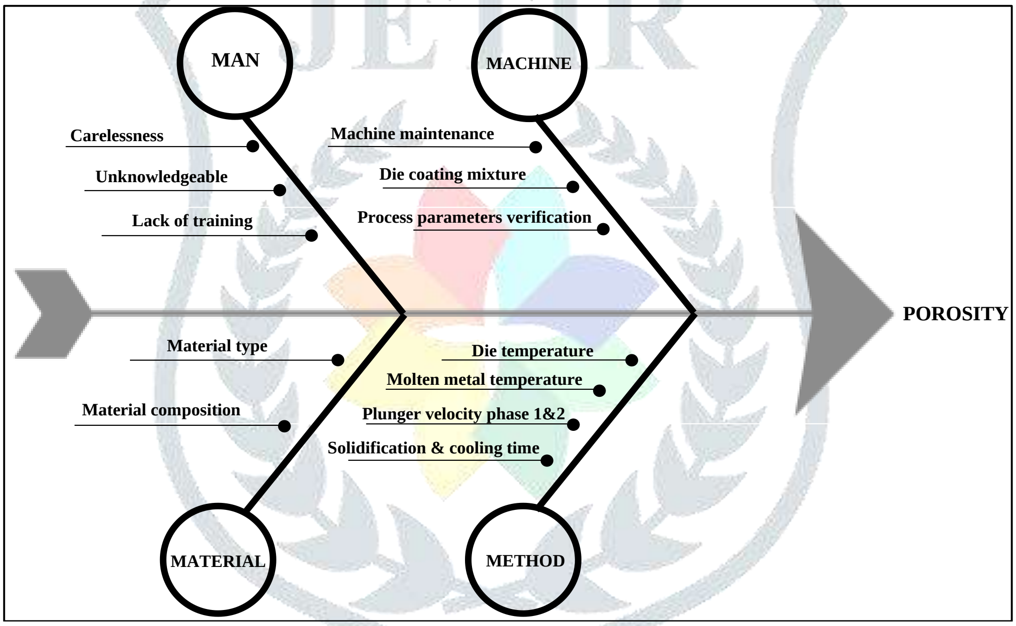

Figure 3. Cause and effect diagram for porosity

3.2.2 Identifying test condition

The test conditions need to be identified. The identified critical factors are the key factors leading to the formation of porosity. These factors were set in 3 different levels as non-linear behaviour of the parameters of a die casting process can be determined only if more than two levels are used. Taguchi also emphasizes on the importance of studying the response variation using signal-to-noise ratio so that the variation due to uncontrollable parameters can be reduced. The signal-to-noise (SN) ratio has been used as one of the quality characteristics. There are 3 main SN ratios available depending on the type of characteristic:

- Nominal-is-best
- Smaller-the-better
- Larger-the-better

As the goal of this project is to reduce the porosity defects, smaller-the-better SN ratio is used here. Next the matrix needs to be designed. The parameters along with their levels are shown in Table 2.

Table 2. Parameter details and their levels

PARAMETER	LEVEL 1	LEVEL 2	LEVEL3	UNIT
Molten metal temperature	610	640	670	ºC
Die temperature	140	160	180	ºC
Plunger velocity phase 1	0.50	0.75	1.00	m/s
Plunger velocity phase 2	1.00	1.50	2.00	m/s

3.2.3 Designing the matrix

After the critical factors are determined, the matrix is developed that will be analyzed in the Minitab software. There are 3 levels for each parameter. Thus, the degree of freedom will be 8 (DOF=experimental runs-1). The design summary is represented in the figure below. Here L9 orthogonal array with 9 experimental runs is selected from the available designs.

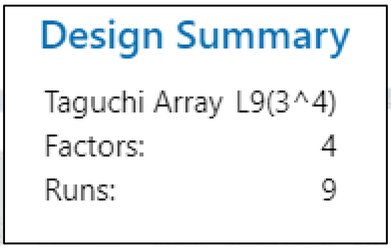

Figure 4. Design summary for DoE

The Taguchi method of design of experiments is used where the SN ratio clones the mean and variation of the quality characteristics. Since the porosity has been selected as the quality characteristic in this investigation, determining the porosity level was very important. The die casted components were manufactured against the trial conditions given in Table 3. Trials were repeated 3 times for each of the combination. The next step was to determine casting porosity accurately. This was done by weighing the castings in air and water using a Mettler balance. Porosity was calculated using the formula:

$$\text{Porosity } (\%) = (1- (\rho_s / \rho_o)) * 100$$

where ρ_s is the measured casting porosity and ρ_o is the porosity of a fully dense casting having no porosity (2.7 g/cm³). The casting porosities for the components were found against the trials. Table 3 also shows the density values and the porosity percentages for each of the trials.

Table 3. Density and Porosity % for the combinations

Molten metal Temperature	Die temperature	Phase 1 velocity	Phase 2 velocity	Density(g/cm³)				Porosity%
				S1	S2	S3	Avg.	
610	140	0.50	1.00	2.4545	2.5056	2.5567	2.5056	7.20
610	160	0.75	1.50	2.5974	2.6327	2.5621	2.5974	3.80
610	180	1.00	2.00	2.5704	2.5603	2.5805	2.5704	4.80
640	140	0.75	2.00	2.5866	2.5513	2.6219	2.5866	4.20
640	160	1.00	1.00	2.5904	2.5500	2.5707	2.5704	4.80
640	180	0.50	1.50	2.5893	2.542	2.6366	2.5893	4.10
670	140	1.00	1.50	2.5623	2.6599	2.4650	2.5624	5.10
670	160	0.50	2.00	2.5731	2.598	2.5411	2.5707	4.79
670	180	0.75	1.00	2.5745	2.534	2.5542	2.5542	5.40

3.2.4 Conducting the experiment

As the goal of this project is to reduce the porosity defects, smaller-the-better SN ratio is used here. The formula used for smaller-the-better is:

$$S/N = -10 * \log (\Sigma (Y 2)/n))$$

Where 'Y' is the response value for each trial repeated 'n' times.

The SN ratios for each trial was calculated and the main effects plot for means, and SN ratios was plotted using Minitab software. Before ANOVA analysis, the effects of each of the parameters can be determined using this plot. The main effects plot compares the means of different parameters in order to determine the optimum level. Here, the four parameters, namely plunger velocity phase 1, and plunger velocity phase 2, die temperature, and molten metal temperature were used to plot. The SN ratio was calculated using the above-mentioned formula. The SN ratios for each trial is depicted in the table below.

Table 4. SN ratio for each of the combinations

Molten metal Temperature	Die temperature	Phase 1 velocity	Phase 2 velocity	Density(g/cm³) Avg.	SN RATIO
610	140	0.5	1	2.5056	-7.9782
610	160	0.75	1.5	2.5974	-8.2907
610	180	1	2	2.5704	-8.2000
640	140	0.75	2	2.5866	-8.2545
640	160	1	1	2.5704	-8.1999
640	180	0.5	1.5	2.5893	-8.2636
670	140	1	1.5	2.5624	-8.1729
670	160	0.5	2	2.5707	-8.2011
670	180	0.75	1	2.5542	-8.1452

The response table shows the direct effect of parameters on response variables (density in this case). The main effects plot represents the response table in a graphical way. The response table along with their main effects plot for SN ratio is shown in the figures below.

Response Table for Signal to Noise Ratios

Smaller is better

Level	Molten metal temperature	Die temperature	V1	V2
1	-8.156	-8.135	-8.148	-8.108
2	-8.239	-8.231	-8.230	-8.242
3	-8.173	-8.203	-8.191	-8.219
Delta	0.083	0.095	0.083	0.135
Rank	3	2	4	1

Figure 5. Response table for SN ratio

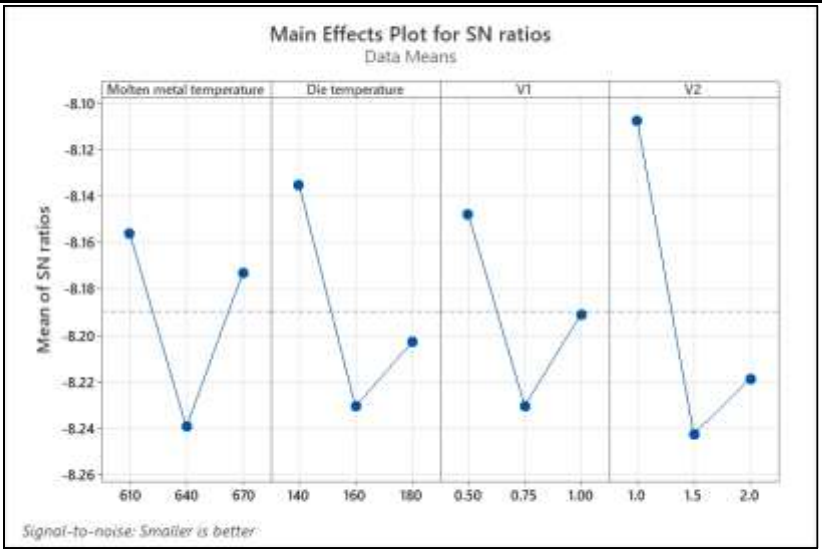

Figure 6. Main effects plot for SN ratio

The parameters molten metal temperature, die temperature, plunger velocity 1st stage and plunger velocity 2nd stage have mean values at three levels. The lower mean values correspond to smaller signal-to-noise ratio. From this analysis, it is evident that the value of each parameter in order to obtain a good quality casting is,

- Molten metal temperature at 640 °C
- Die temperature at 160 °C
- Plunger velocity 1st phase at 0.75 m/s
- Plunger velocity 2nd phase at 1.5 m/s

After obtaining optimum level, ANOVA analysis was done which shows the process parameters that affect the quality characteristic the most. Results obtained for density from ANOVA is shown in Table 5. The table shows that Plunger velocity phase 2 is the most influential factor that affects density the most followed by die temperature.

Table 5. Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	% Contribution
Molten metal temperature	2	0.011569	0.011569	0.005784	17.213
Die temperature	2	0.014441	0.014441	0.007220	21.490
V1	2	0.010222	0.010222	0.005111	15.209
V2	2	0.030983	0.030983	0.015491	46.088
Residual Error	0	*	*	*	
Total	8	0.067214			

IV. Results

The optimal levels were found at

- Level 2 – molten metal temperature (640 °C)
- Level 2 – die temperature (160 °C)
- Level 2 – plunger velocity phase 1 (0.75 m/s)
- Level 2 – plunger velocity phase 2 (1.5 m/s)

Utilizing Taguchi’s prediction model, the predicted value for the density was found by incorporating the optimal setting.

Table 6. Predicted mean and SN ratio

S.no	Parameter	Optimal setting	Predicted mean	Predicted SN ratio
1	Molten metal temperature	640	2.63	-8.37
2	Die temperature	160		
3	Plunger velocity phase 1	0.75		
4	Plunger velocity phase 2	1.5		

The predicted density is found to be 2.62169 and the SN ratio to be -8.37381. This result was obtained from incorporating the optimal levels of factors.

Table 7. Predicted porosity %

Predicted Density Value (g/cm³)	Standard Density Value(g/cm³)	Porosity (%) = (1- (ρ_s/ ρ_o)) * 100
2.62169	2.7	2.9

V. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

To summarize, die casting is one of the largely used advancements in the metal forming process. As client requests for higher accuracy, better quality and efficiency in the current situation, improving the quality is of main concern for every one of the producers. This project stresses on the utilization of quality tools for scrutinizing the reasons for the deformities, the Taguchi method for DoE. Lastly, all of the above-mentioned techniques were used in such to obtain the optimal process parametric combination to reduce the percentage of porosity rejections.

The key inferences that can be obtained from this project are:

- The utilization of quality tools such as fishbone or Ishikawa diagram and pareto chart to break down and investigate the reasons for the deformities. Only after using the cause-and-effect diagram and pareto chart, the critical factors could be narrowed down. So, the use of quality tools is of great importance.
- Taguchi's Design of Experiments helped in enhancing the process parameters and also in reducing the time of computation. DoE was performed with the use of Minitab software. The optimal values obtained is believed to be robust to the environment. The optimal setting of parameters was found at level 2 of all the factors.
- ANOVA was used to determine the independent parameter that had the most influence on the dependent parameter. The results from ANOVA showed that plunger velocity phase 2 was the most influential parameter on porosity.
- The predicted value of density for the optimal setting of parameters was found to be 2.62169 g/cm³ and when compared to its standard value, the porosity percentage was reduced to 2.9% from almost 4%.

5.2 Future scope

Although design of experiments provided a predicted value of density for the optimal setting and proved to be useful for optimization, there needs to be further works done in order to verify and improve the condition even more. The future work include:

- Implementing the obtained optimal setting for the parameters in the die casting machine and performing a 3-hour production run in the shop floor.
- Checking for the occurrence of porosity and other types of defects after machining in the turning and milling centers.
- Key dimension that is inspected is selected and process capability analysis is done for the same. Control charts are constructed with upper and lower control limits.
- Using lean methodologies such as kaizen, Kanban, Gemba, and 5S to improve the working conditions of the entire die casting unit and its surroundings.

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