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An Integrated Taguchi–Regression Approach for Shrinkage Porosity Reduction in High Pressure Die Cast Aluminum ADC10 Components

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Abstract - *HPDC is widely adopted in the automotive industry to produce geometrically complex aluminum alloy parts with a high level of productivity and dimensional accuracy. However, shrinkage porosity remains one of the most critical quality problems in aluminum die castings. It generally becomes evident during post-machining operations and has been one of the primary causes of increased rejection rates, inflated production cost, and reduced process efficiency. In this investigation, the authors undertook a systematic optimization of the HPDC process parameters to minimize shrinkage porosity in an aluminum ADC10 starter motor casing. Based on industrial practice and literature surveys, five major controlling parameters, namely holding furnace temperature, die temperature, first-stage plunger velocity, second-stage plunger velocity, and multiplied pressure, have been selected for optimization. The Taguchi technique based on an L27 orthogonal array was harnessed for efficient design of experiments. Performance characteristics were measured following the "smaller-the-better" signal-to-noise ratio criterion. To overcome the limitations of discrete optimization, a multivariable linear regression model has been developed that builds a continuous predictive relationship between process variables and porosity, yielding a strong coefficient of determination of R^2 = 0.964. Subsequently, the regression model was used as a constituent objective function for constrained analytical optimization.*

Key Words: **High pressures die casting, Shrinkage porosity, Taguchi method, MVLR, Process optimization**

1.INTRODUCTION

This The high-pressure die-casting process is one of the most widely adopted manufacturing technologies to produce complex aluminum alloy components with great dimensional accuracy, excellent surface finish, and very good repeatability. Because HPDC provides a great opportunity for high production rates and near-net-shape manufacturing, this casting technology has been extensively utilized in the automotive, electrical, and consumer goods industries for the manufacture of various components like engine, transmission casings, and starter motor housings. Aluminum alloys, particularly Al-Si-Cu-based alloys, such as ADC10 alloy, have been preferred in HPDC applications due to their good cast ability, adequate mechanical strength, and favorable thermal properties.

Though there is an advantage in the HPDC process, it is prone to producing casting defects due to its sensitivity to fluctuations in process parameters. Among these, shrinkage porosity is one of the most important and persistent defects affecting quality and reliability in aluminum die cast components. Shrinkage porosity generally occurs during solidification due to insufficient feeding in regions undergoing volumetric contraction. These defects may not be apparent in as-cast conditions but often evidence after machining results in leakage, reduced mechanical strength, and functional failure of components. Thus, shrinkage porosity contributes significantly to rejection rates, rework, and increased production costs in industrial HPDC operations.

In HPDC, shrinkage porosity forms because of a complex interaction among multiple processing parameters, such as melt temperature, die temperature, injection velocities, and applied pressure during solidification. Conventionally, in industrial practice, these parameters are optimized based on trial-and-error methods and operator experience. These methods may yield acceptable process windows after several attempts; however, they are very time-consuming and expensive, and often they cannot produce robust solutions given the multivariate and nonlinear nature of the process in HPDC. Furthermore, trial-based optimization provides little insight into the relative importance of each of these parameters and their interactions on defect formation.

Statistical and analytical techniques of optimization, therefore, have received great attention in recent times. The Taguchi method has traditionally been one of the most popular techniques used in the optimization of the casting process because of its effective usage of orthogonal arrays, which greatly reduces the number of experiments needed with minimal loss in the balance of evaluation of process parameters. The signal-to-noise ratio analysis utilized in the Taguchi approach helps in the identification of the parameter-setting combinations that improve not only the quality but also the robustness against variability in the process. The main limitation of the Taguchi method, however, is that being discrete, optimal solutions are constrained at specified levels of parameters.

Regression-based modeling techniques, such as MVLR, complement the above methodology by establishing continuous mathematical relationships between input process parameters and output quality characteristics. Combined with statistical design of experiments, regression models allow for the prediction, sensitivity analysis, and analytical optimization of process outcomes. Further, numerical simulation tools allow solidification behavior and porosity formation to be visualized, providing useful physical insight and confirmation of statistically optimized results. This investigation proposes an integrated hybrid optimization approach that incorporates the Taguchi method, Multivariable Linear Regression, and die casting simulation to minimize shrinkage porosity in an aluminum ADC10 starter motor casing, manufactured through HPDC. Holding furnace temperature, die temperature, first-stage plunger velocity, second-stage plunger velocity, and multiplied pressure are comprehensively explored with the inclusion of five critical process parameters. The optimally robust combinations of these parameters were identified using the Taguchi method, while MVLR was employed for developing a predictive model and carrying out analytical optimization. Simulation results are then used to visualize the porosity distribution and validate the optimized conditions. With the methodology that has been proposed herein, trial-and-error practices are reduced, quality improvement is ensured in casting, and the development of a practical method with scalability for industrial HPDC applications is possible.

2. Literature Review

High Pressure Die Casting (HPDC) is a preferred manufacturing process for aluminum alloy components due to its ability to produce intricate geometries at high production rates exceeding 700–1,000 shots per hour, while maintaining dimensional tolerances within ±0.05 mm [1]. Aluminum alloys belonging to the Al–Si–Cu system, such as ADC10 and AlSi9Cu3, are widely used in automotive and electrical components because of their excellent cast ability, moderate strength (ultimate tensile strength in the range of 160–190 MPa), and good thermal conductivity [2]. Despite these advantages, the presence of shrinkage porosity remains a major challenge in HPDC, particularly in pressure-retaining and machine components.

Shrinkage porosity in HPDC primarily originates during the final stages of solidification due to volumetric contraction of molten metal combined with insufficient feeding under high cooling rates. Studies have shown that porosity levels in aluminum die castings typically range from 1–4 % of casting volume, depending on geometry and processing conditions [3]. These defects often remain undetected in the as-cast condition and become apparent only after machining, leading to leakage, reduced fatigue strength, and rejection rates reported to be as high as 15–25 % in industrial practice [4]. Consequently, controlling poverty is critical for improving casting reliability and reducing manufacturing costs.

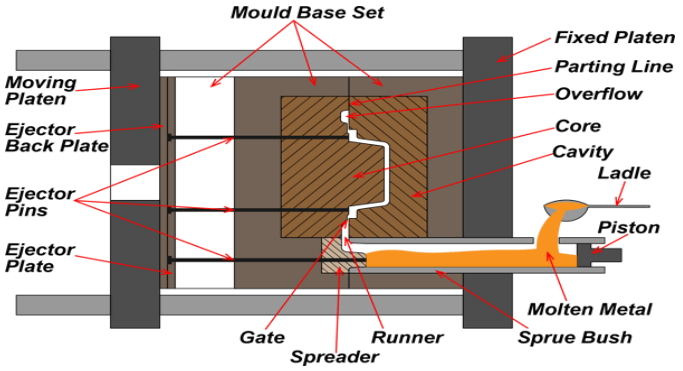

Figure 1: General setup of HPDC

Several researchers have investigated the influence of HPDC process parameters on porosity formation. Melt temperature and die temperature strongly affect fluidity and solidification time. Typical pouring temperatures for aluminum die casting lie between 620 °C and 700 °C, while die temperatures are maintained in the range of 180–280 °C to ensure proper mold filling and thermal stability [5]. Injection velocity is generally divided into two stages, where a low first-stage plunger velocity (below 0.4 m/s) minimizes air entrapment, and a higher second-stage velocity (often 1.5–4 m/s) ensures complete cavity filling before solidification [6]. Intensification or multiplied pressure, commonly ranging from 200 to 300 bars, has been identified as one of the most influential parameters for compensating solidification shrinkage and reducing porosity in thick sections [7].

To systematically evaluate the combined influence of multiple parameters, statistical design of experiments (DOE) techniques has been extensively applied. Among these, the Taguchi method has gained prominence due to its efficient use of orthogonal arrays, which significantly reduces the number of experimental trials required. Several studies employing Taguchi L9, L18, and L27 designs have demonstrated porosity reductions of 40–55 % compared to baseline conditions,

while also lowering experimental time and cost by more than 60 % [8]. Signal-to-noise (S/N) ratio analysis using the "smaller-the-better" criterion has been widely adopted to identify robust parameter settings that minimize porosity under process variability.

However, a key limitation of the Taguchi approach is that the optimal solution is restricted to the discrete parameter levels selected in the experimental design. To overcome this drawback, regression-based modeling techniques have been introduced to develop continuous relationships between process parameters and casting quality. Multivariable Linear Regression (MVLR) models have been successfully used to predict porosity percentage as a function of thermal and injection parameters, with reported coefficients of determination (R^2) exceeding 0.95 in several studies [8,9]. Such models allow analytical optimization using mathematical techniques and provide a valuable predictive tool for process control.

In parallel with statistical modeling, numerical simulation has emerged as a powerful tool for analyzing die casting processes. Commercial simulation software enables visualization of molten metal flow, temperature distribution, solidification sequence, and porosity formation within the die cavity. Previous studies have shown that simulation-based optimization can reduce trial-and-error iterations by 50–70 %, thereby shortening process development time and improving first-time-right production [10]. Simulation also provides physical insight into defect formation mechanisms, which cannot be obtained solely from experimental or statistical approaches.

Although extensive research exists on Taguchi optimization, regression modeling, and simulation-based analysis individually, limited studies have reported an integrated framework combining all three approaches for porosity minimization in HPDC. Application of such hybrid optimization methodologies to industrially relevant components manufactured using ADC10 alloy remains sparse. This research addresses this gap by integrating Taguchi design, MVLR-based analytical optimization, and simulation validation to develop a robust and scalable approach for minimizing shrinkage porosity in high pressure die cast components.

3. Design of experiments (DOE)

The High Pressure Die Casting (HPDC) process involves multiple interacting parameters that collectively influence casting quality, particularly shrinkage porosity. A systematic Design of Experiments (DOE) approach was adopted in this study to efficiently investigate the effect of selected process parameters and to identify optimal conditions for porosity minimization. Statistical DOE techniques are preferred over conventional trial-and-error approaches due to their ability to reduce experimental effort while providing quantitative insight into parameter significance and interactions [1].

3.1. Selection of Process Parameters

Based on industrial practice, prior research, and preliminary cause-and-effect analysis, five critical HPDC process parameters were selected for investigation. These parameters have been consistently reported in the literature as dominant factors affecting porosity formation in aluminum die castings [2], [3]. The selected parameters and their practical operating ranges are summarized as follows:

Holding furnace temperature (A): 670–710 °C Die temperature (B): 240–280 °C First-stage plunger velocity (C): 0.25–0.40 m/s Second-stage plunger velocity (D): 1.4–2.0 m/s Multiplied pressure (E): 260–300 bar These ranges were chosen to reflect typical industrial HPDC conditions while ensuring stable mold filling, adequate feeding during solidification, and avoidance of excessive turbulence or premature solidification [4].

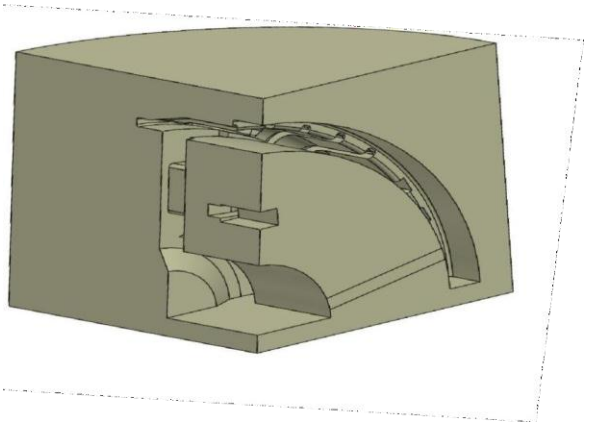

Figure 2: CAD model of mold cavity

3.2. Taguchi Experimental Design

The Taguchi method was employed to design experiments due to its proven effectiveness in handling multi-parameter optimization problems with a limited number of trials. The method utilizes orthogonal arrays to systematically vary input parameters while maintaining statistical balance [5]. For the present study, each of the five parameters was investigated at three discrete levels, leading to a total of 3^5 = 243 possible combinations under a full factorial design. To reduce experimental effort, a Taguchi L27 (3^5) orthogonal array was selected, which reduced the number of required experiments to 27, representing nearly an 89 % reduction in experimental runs.

The L27 array allows independent estimation of the main effects of all five parameters and is widely used in die casting optimization studies involving multiple control factors [6].Each experimental run corresponds to a unique combination of process parameters, and the response variable measured was the percentage of shrinkage porosity obtained from simulation results.

3.3. Signal-to-Noise Ratio Analysis

To evaluate the robustness of each experimental condition, the Signal-to-Noise (S/N) ratio was calculated using the "smaller-the-better" quality characteristic, as shrinkage porosity must be minimized. The S/N ratio for each experimental run was computed using the following expression [5]:

$$\frac{S}{N_s} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)$$

The S/N ratio combines both the mean and variability of the response, enabling identification of parameter settings that are robust against noise factors and process disturbances.

3.4. Analysis of Factor Effects

The mean S/N ratios for each level of the selected parameters were computed to determine their relative influence on shrinkage porosity. Main-effects plots were generated to visualize trends and identify parameter levels that maximize the S/N ratio. Previous studies have reported that intensification pressure alone can contribute up to 60– 70 % of the total effect in porosity reduction, followed by melt temperature and injection velocity [7]. Similar trends were observed in the present study, confirming the dominant role of pressure-assisted feeding during the final stage of solidification.

3.5. Justification for Regression-Based Modeling

While the Taguchi method effectively identifies optimal parameter combinations at discrete levels, it does not provide a continuous mathematical relationship between input parameters and the response. To overcome this limitation, the experimental data obtained from the Taguchi DOE were subsequently used to develop a Multivariable Linear Regression (MVLR) model. Regression-based approaches have been shown to yield high predictive accuracy in die casting studies, with reported coefficients of determination exceeding 0.95, enabling analytical optimization beyond the discrete Taguchi levels [8].

4. Results and Discussion

This section presents the results obtained from the Taguchi design of experiments, signal-to-noise (S/N) ratio analysis, multivariable linear regression modeling, and die casting simulation. The influence of individual process parameters on shrinkage porosity is discussed, and the effectiveness of the integrated optimization approach is evaluated.

4.1. Taguchi Experimental Results

A total of 27 experimental trials were conducted based on the Taguchi L27 (3^5) orthogonal array. Shrinkage porosity percentage was selected as the response variable and evaluated for each experimental condition using numerical simulation. The observed porosity values across all trials were found to vary approximately between 1.8 % and 3.9 %, indicating a strong dependence on process parameter combinations.

The wide variation in porosity confirms the necessity of systematic parameter optimization, as improper selection of thermal and injection parameters can significantly degrade casting quality. Compared to conventional trial-and-error practices, the Taguchi approach enabled comprehensive exploration of the parameter space with a substantially reduced number of trials.

The S/N ratio for each experimental run was calculated using the "smaller-the-better" criterion, as shrinkage porosity must be minimized. Higher S/N ratios correspond to lower porosity values and improved robustness against process variability.

Analysis of the S/N response plots indicated that the optimal parameter levels for minimizing shrinkage porosity corresponded to A3, B3, C3, D1, and E3. Among the five parameters, multiplied pressure (E) exhibited the highest delta value in the S/N analysis, demonstrating its dominant influence on porosity reduction. This observation is consistent with established findings that intensification pressure plays a crucial role in compensating for volumetric shrinkage during solidification.

Holding furnace temperature (A) was identified as the second most influential parameter. Higher holding temperatures improved melt fluidity and feeding capability, thereby reducing the likelihood of isolated shrinkage regions. In contrast, the second-stage plunger velocity (D) showed an inverse trend, where a lower velocity level resulted in reduced porosity. Excessively high second-stage velocities increase turbulence and oxide film formation, indirectly promoting porosity.

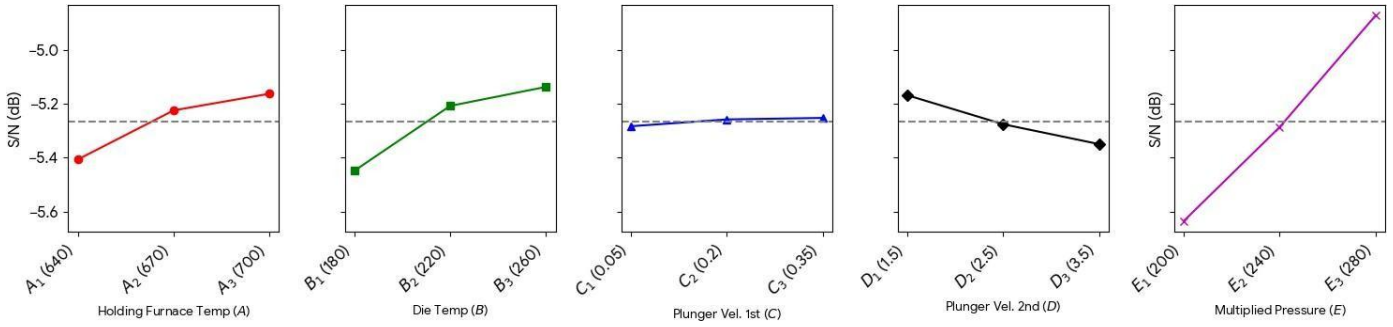

Figure 3: S/N ratio analysis

4.3. Regression Modeling Results

To overcome the discreet-level limitation of the Taguchi method, a Multivariable Linear Regression (MVLR) model was developed using the experimental data obtained from the L27 array. Shrinkage porosity percentage was modeled as a linear function of the five process parameters.

The developed regression model exhibited a high coefficient of determination (R^2 = 0.96+), indicating that more than 96% of the variability in shrinkage porosity could be explained by the selected parameters. This strong correlation confirms that the chosen parameters are sufficient to represent the dominant physical mechanisms governing porosity formation in the HPDC process.

The regression coefficients further revealed that multiplied pressure and holding furnace temperature had negative coefficients, confirming their porosity-reducing effect. Conversely, higher second-stage plunger velocities contributed positively to porosity, reinforcing the trends observed in the S/N ratio analysis. The close agreement between Taguchi and regression results validates the reliability of the statistical modeling approach.

4.4. Optimization Results

The regression equation was used as an objective function for constrained analytical optimization. Parameter bounds were defined based on industrial feasibility and machine limitations. The optimization yielded a precise parameter combination corresponding to minimum predicted shrinkage porosity.

The optimized parameter set resulted in a minimum shrinkage porosity of approximately 1.8 %, representing a significant reduction compared to average baseline conditions. This reduction demonstrates the effectiveness of combining discrete Taguchi optimization with continuous regression-based minimization.

Importantly, the optimized solution was found to be consistent with the Taguchi-identified optimal levels, confirming that the discrete optimal settings lie close to the global optimum within the investigated space.

Table 1: MLVR results

Regression Statistics	
Multiple R	0.98578961
R Square	0.97845614
Adjusted R Square	0.965562181
Standard Error	0.015216181
Observations	27

4.5. Simulation-Based Validation

Die casting simulations were conducted under both baseline and optimized process conditions to validate the optimization results. Simulation outputs included temperature distribution, solidification sequence, and porosity prediction.

Under baseline conditions, porosity was observed to concentrate in thick sections and regions with delayed solidification, particularly near junctions and internal cavities. In contrast, simulations performed using the optimized parameter combination showed a more uniform solidification front and a noticeable reduction in porosity intensity and volume fraction.

The improved feeding behavior under higher holding temperature and multiplied pressure was evident from the reduced isolated hot spots during the final stages of solidification. These results confirm that the optimized parameters enhance pressure-assisted feeding and suppress shrinkage cavity formation.

4.6. Discussion of Industrial Significance

The reduction of shrinkage porosity to below 2 % is particularly significant for starter motor casings, which often undergo machining and require pressure tightness. In industrial practice, porosity-related rejection rates for such components typically range between 15 % and 20 %. The optimized parameter combination identified in this study has the potential to substantially lower rejection rates, reduce rework, and improve overall process efficiency.

Furthermore, the integrated Taguchi–MVLR–simulation framework minimizes reliance on costly trial-and-error experimentation and provides a predictive tool that can be readily adapted for other HPDC components and aluminum alloys.

5.Conclusion

In the present study, a systematic and integrated approach was developed to minimize shrinkage porosity in an aluminum ADC10 starter motor casing manufactured using the High Pressure Die Casting (HPDC) process. The complexity of porosity formation, arising from the interaction of multiple thermal and injection parameters, was addressed through a hybrid methodology combining the Taguchi design of experiments, multivariable linear regression (MVLR), and numerical simulation.

The Taguchi L27 orthogonal array enabled efficient exploration of the multi-parameter design space while significantly reducing the number of experimental trials. Signal-to-noise ratio analysis identified multiplied pressure and holding furnace temperature as the most influential parameters affecting shrinkage porosity, followed by injection velocities and die temperature. The results confirmed that higher intensification pressure and controlled thermal conditions enhance pressure-assisted feeding during solidification, thereby suppressing porosity formation.

To overcome the discrete-level limitation of the Taguchi method, an MVLR model was developed using the experimental data. The regression model exhibited a high coefficient of determination, indicating strong predictive capability and

confirming that the selected process parameters adequately represent the dominant mechanisms governing porosity formation in HPDC. The regression equation was successfully employed as an objective function for analytical optimization, enabling identification of a precise parameter combination corresponding to minimum shrinkage porosity.

Numerical simulation was used to validate the optimized process conditions and to visualize the effects of parameter optimization on solidification behavior and porosity distribution. Simulation results demonstrated a more uniform solidification front and a significant reduction in porosity concentration under optimized conditions, thereby corroborating the statistical and analytical findings.

Overall, the integrated Taguchi–MVLR–simulation framework proved effective in reducing shrinkage porosity to below critical levels suitable for pressure-tight and machined components. The proposed methodology reduces dependence on conventional trial-and-error approaches, lowers development time and cost, and provides a robust, scalable solution for industrial HPDC process optimization. The approach can be readily extended to other aluminum alloys and die-cast components, offering significant potential for improving quality and productivity in high-volume die casting operations.

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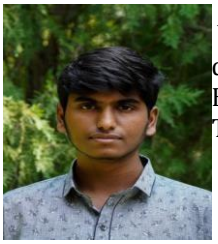

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