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INFLUENCE OF CAD AND CAE IN CASTING PROCESS

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ABSTRACT

This paper discusses the use of CAE in aluminum HPDC, focusing on its effectiveness and efficiency in terms of enhancing reliability and quality. CAE de-emphasizes the trial-and-error methods that characterize most conventional approaches since it uses the state-of-the-art numerical modeling tools, such as AnyCasting and ProCAST, that optimize critical casting parameters, including gate and runner design, pouring temperature, mold temperature, and injection speed, to achieve improved mechanical properties in terms of tensile strength and elongation, while reducing internal defects .A number of simulations can predict filling and solidification problems, optimized gating systems, and layouts with minimal defects, hence cost reduction. It also integrates casting advancements for a variety of alloys, including the ADC12, A356, and titanium. A CAD-based methodology is introduced by combining both design and manufacturing stages through optimized simulations in analyzing stresses, heat transfer, and material flow. This proactive approach allows for defect prediction and elimination before production, enhancing the structural integrity of components. This research thus shows how CAE and innovative CA-FEA methods boost manufacturability and minimize wastes, thereby being a relevant tool in producing castings that are high quality and, thus, meet the needs of such diverse industries as automotive, wind turbines, and domestic appliances.

Keywords: CAE, CAD, HPDC, AnyCasting, ProCast, Design.

I. INTRODUCTION

High-pressure die casting, HPDC is a production process that produces precision high-quality parts in mass quantity. The association of CAD and CAE greatly improved the efficiency, accuracy, and cost-effectiveness of HPDC processes. More design geometries of the components, molds, and dies are oriented for CAD for HPDC. More CAD tools are applied in the development of high-resolution 3D models that represent the kind of complex shapes and geometries expected in HPDC. CAD offers rapid prototyping where designs can be examined and optimized before the actual production process begins. Popular software offers to facilitate easy iterations in design, thereby keeping development time to a minimum and reducing errors in designs. HPDC CAE content deals with the cast process simulation and optimization. Using these tools HPDC engineers analyse such aspects like the flow of molten metal, and cooling after solidification. The result of flow simulations ensures that the molds fill up equally to prevent defects like cold shuts and air entrapment. Doing thermal simulations optimizes both cooling rates and warping and residual stresses. Besides, by the process of casting the components, an operation load casts those under the CAE tool for testing of their integrity. Such analyses use the following software: ANSYS, MAGMASOFT, and ProCAST.Figure-1 shows the Integration of CAD & CAE in casting process.CAD and CAE integration assist an engineer to design robust structural forms and optimize HPDC parameters before production as against trial-and-error approaches. It impacts quality products effectively, reduces the length of production cycles, and decreases manufacturing cost. Currently, CAD and CAE cannot be substituted in operations for HPDC so that it meets the stringent demands for precision and efficiency.

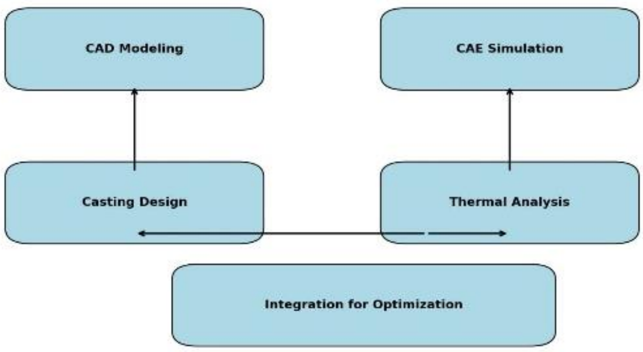

Figure 1: Integration of CAD & CAE in casting process

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II. METHODOLOGY

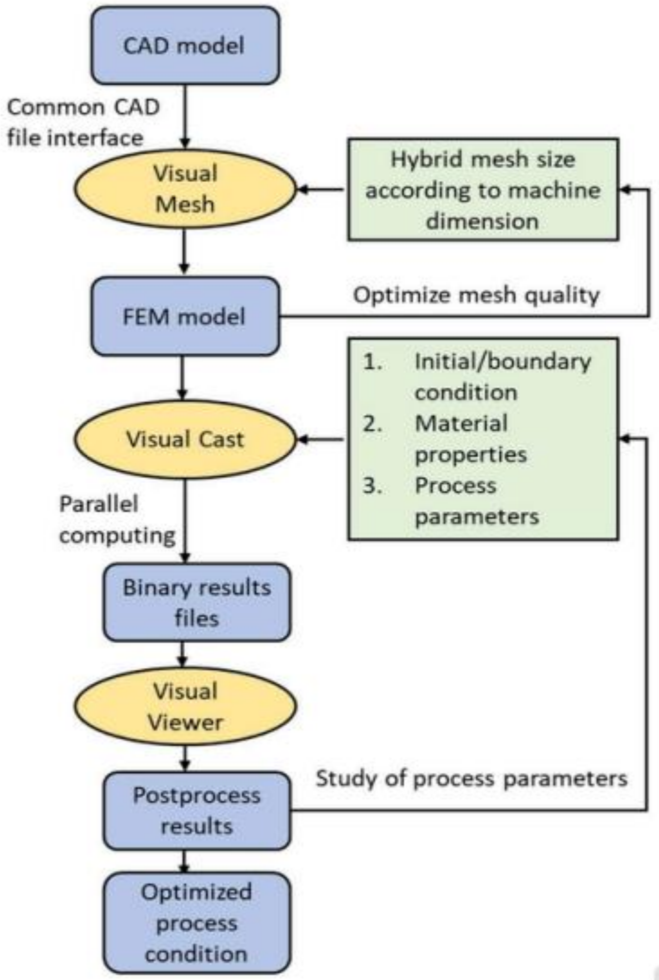


Figure 2: Workflow of the HPDC casting process

Design of the model using CAD

One of the steps in a casting process simulation workflow is a CAD model, which is also the initial phase. A CAD file is created from a computer-aided design (CAD) software that shows the part may be cast and its geometric design. This step is crucial as the CAD model defines the exact dimensions, shape and structural characteristics of the part ensuring that it meets manufacturing and performance criteria. This workflow first exports the CAD model via a common CAD file interface (STEP, IGES or STL format) ensuring that it will be compatible with subsequent processes.

This model is then fed into the Visual Mesh module for meshing. Wherein, he also need to mesh the geometry accurately, because he aims to convert this CAD geometry into finite element model (FEM) which can be used for purpose of FEM Simulations. Quality of cad model directly effects the efficiency of whole casting operation. An appropriate design minimizes defects such as porosity, shrinkage or warp while ensuring the casting has required physical properties. In addition, the CAD model may also contain design features related to the casting process, e.g., draft angles, fillets and allowances (e.g. shrinkage and machining).

The CAD model is used in the simulation environment that easily integrates into which provides visualization of component geometry, efficient analysis and process optimization, making it possible to manufacture defect-free cast components of high quality. This step helps you develop a perfect casting process & is especially essential in making accurate simulations.

Mesh generation using FEM

Visual Mesh module of the workflow which is responsible for creating a computational mesh to prepare CAD model for simulation. In this process, the geometric shredding of the component should be done so that it passes through FEM. To actuate physical processes such as heat transfer and material movement during casting, the model is discretized using a mesh, which represents a network of interconnected elements and nodes. In this method, the Visual Mesh combines different element types (tetrahedral and hexahedral) to make a hybrid mesh to optimize both simulation accuracy and computing efficiency. Depending on the geometry of the part and size of machine, adjusting the mesh size. Coarse meshes are employed in relatively unimportant regions to reduce computational load while fine meshes are used in region which requires detailed analysis.

An important process involves mesh quality optimization, ensuring the element well-shaped and equally distributed. A good mesh quality is important, as poor mesh can lead to false results or simulated problems with convergence. Optimization is the art of reducing element distortion, maintaining a continuous transition from areas with coarse mesh to finer and ensuring constant size elements where required. The Visual Mesh ensures that the FEM model accurately represents important parameters such as temperature gradients, stress distributions and liquid metal flow by generating a quality mesh. This stage provides the fidelity necessary for additional research and development on casting simulations, while establishing a foundation that maintains accurate casting simulations.

Visualization of the casting process

The Visual Cast module is a critical component of the workflow used to model the casting process and enable studying and tuning important parameters. Using this together with other data, the Visual Cast mimics the casting processes which are inherently complex in their physical nature, after a finite element model (FEM) has been developed using mesh generated from the Visual Mesh module. These are the: potential creation of flaws, heat transfer during solidification and movement of molten metal. This module consists of key inputs such as material properties, process parameters, and initial and boundary conditions. This means the interactions of the metal with the mold -and everything else such as temperatures, flow rates and thermal gradients- are given in terms of initial and boundary conditions. Things like density, viscosity, heat conductivity are material characteristics that are needed so that the behavior of the metal and the mould materials can be well simulated. The simulation is then honed in on for specific casting conditions using process variables such as pouring temperature, cooling rates of the mold, and gating system design. Parallel computing is used by the Visual Cast to efficiently manage these complicated calculations. It reduces computation time by distributing tasks across multiple processors while maintaining high accuracy. Result from the simulation was saved in binary files include full information on solidification, temperature field and predicted defect caused by shrinkage or porosity. This modeling step allows engineers to test how the casting process will behave under specific conditions and identify potential issues before conducting real trials. Thus, the Visual Cast module is the key to ensure soundness and quality of the casting process, greatly reducing manufacturing trial-and-error.

Results & Analyzing the process

At the last stage of casting simulation is the workflow called Postprocess Results, which is the last but most valuable step of casting simulation since it takes out the valuable information gotten from the Visual Cast module during simulation. This means interpretation of results in simulation performance evaluation and finding possible development areas.The final binary result files from running the simulation are loaded up using a postprocessing program like Visual Viewer for closer inspection. Main results of the simulation are examined to determine temperature gradients, solidification patterns, stress distributions, defect formation, among others, such as porosity, shrinkage voids, or hot spots.This research can aid engineers in understanding literally how molten metal moves through the mold, how heat is transported, and how it solidifies, and hence postprocessing insights are needed for the optimization of the casting process. For example: identification of shrinkage or porosity-susceptible areas and their elimination. Process parameter changes, such as cooling speed, pouring temperature, or gating system design, are also a part of process design to minimize defects and optimize material flow. Mold redesign.

Engineers can further improve the quality and productivity of the casting process in accordance with their interpretation of results and subsequent decisions. Finally, after such repeated cycles of analysis and improvement, the optimal condition of the process is achieved such that the obtained cast components satisfy requirements on quality and specifications of the design. In this way, the Postprocess Results step closes the cycle by relating the simulation to the actual process improvement.

Optimization

It is at the Optimized Process Condition that final simulation workflow of casting uses all postprocessing insights to improvise and tweak the casting procedure. This step ensures waste and manufacturing costs are reduced, while the casting operation is also assured to work with high efficiency, few flaws, and such quality requirements. This culminates in some postprocessing of the data analysis results in modifying the key parameters of the casting process.

They could include:

Pouring temperature: This ensures that molten metal flows into the mold without hesitation and does not solidify too soon.

Cooling rates: Synchronization of solidification is controlled to avoid defects like thermal stress or shrinkage cavities.

Design the gating and riser: To improve the flowability of molten metal, significantly reduce turbulence, and minimize porosity or inclusions by positioning the mold.

Some design changes can further be applied on the mold design to the possible weak points that may result due to simulation, such as fillets, draft angles, or wall thicknesses. The modified process parameters find a balance between the quality of the final product and manufacturing feasibility. More simulations or physical tests are done to validate the optimum values and that the changes made are enough to help in healing those defects identified earlier on. In physical manufacturing, this iterative approach reduces costly trial-and-error and material waste. With a Process Condition now optimized, casting becomes stronger and more reliable, enabling to produce components of the highest quality and free defects. Passing from design to manufacturing through this stage increases industrial production productivity and cuts lead times in addition to these results.

III. MODELING AND ANALYSIS

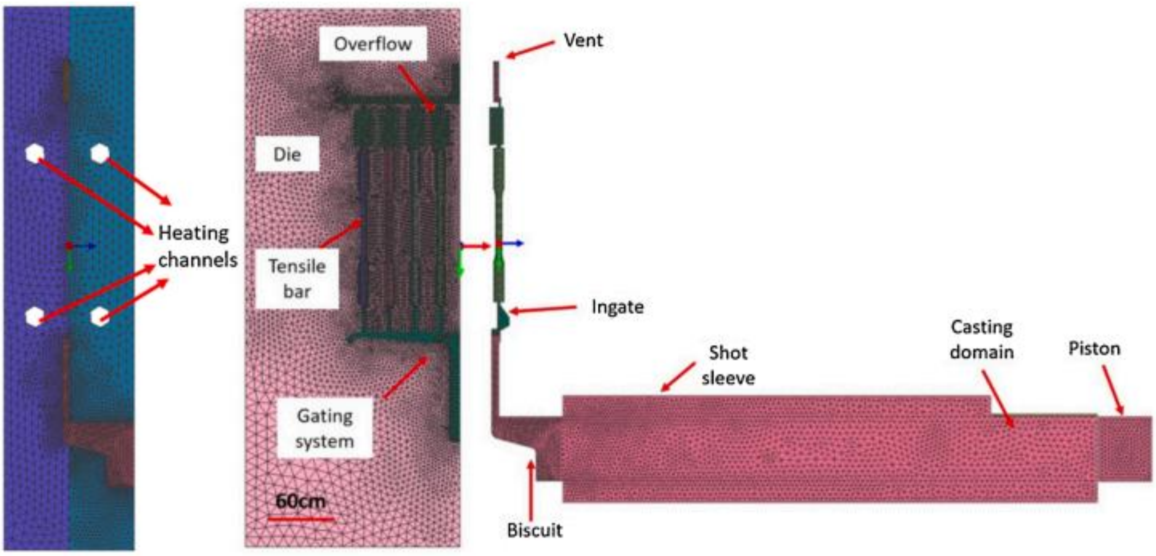


Figure 3: Mesh generation of the HPDC CAD design model

Mesh generation of the cad model

The High-Pressure Die Casting process is modeled by discretizing a geometrical model into a mesh by the Finite Element Method. By doing this, detailed analysis on fluid flow, heat transfer, and solidification can be carried out inside the die cavity. The geometrical model of the HPDC system is created with CAD software, adequately reflecting the physical characteristics of the casting system and, in itself, having the main influence on the accuracy of the simulation. The half-model approach allows for improved computational efficiency without time-consuming computations with such immense simulation complexity, keeping reliable results for the whole system.

Numerical modelling

To Understand how liquid metal flows, cools, and solidifies during the process of High Pressure Die Casting (HPDC) is required. These equations help predict what will happen to the material during the casting process.

Continuity equation:

$$\frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l \langle \mathbf{v}_l \rangle) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\frac{\rho_l}{g}\mathbf{v}_l\right) + \nabla \cdot \left(\frac{\rho_l}{g^2}\mathbf{v}_l \mathbf{v}_l\right) + \nabla p - \nabla \cdot \left(\frac{\mu_l^{eff}}{g}\left[\nabla \mathbf{v}_l + \nabla \mathbf{v}_l^T\right]\right) = \rho \mathbf{g} - \mu_l K^{-1} \mathbf{v}_l \quad (2)$$

Energy equations:

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho g\, h\, \langle \mathbf{v}_l \rangle) = \nabla \cdot (\kappa \nabla T) + S \quad (3)$$

$$h(T) = \int_0^T C_P(T)dT + L(1 - f_s(T)) \quad (4)$$

$$div(\rho_l g \mathbf{v}_l) - \rho_l \frac{\partial g_p}{\partial t} = -\frac{\partial \langle \rho \rangle}{\partial T}\frac{\partial T}{\partial t} \quad (5)$$

$$g_l = 1 - g_s - g_p \quad (6)$$

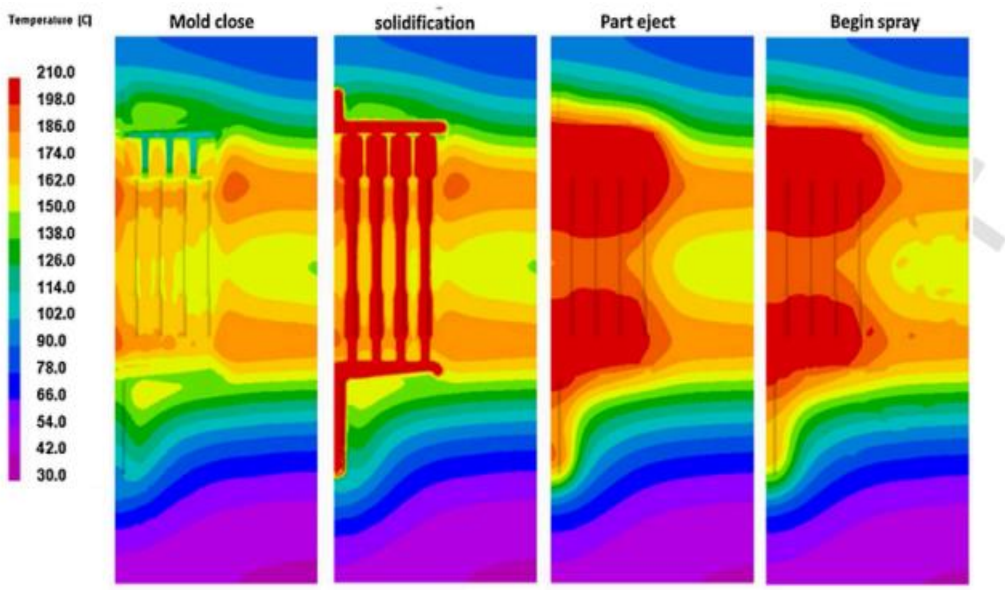
$$div\left[\rho_l \frac{K}{\mu}(\nabla p_l - \rho_l \mathbf{g})\right] + \rho_l \frac{\partial g_p}{\partial t} = \frac{\partial \langle \rho \rangle}{\partial T}\frac{\partial T}{\partial t} \quad (7)$$

Simulation of the casting

Numerous calibration experiments are conducted to ensure that the simulation model realistically simulates conditions at the HPDC stage. Calibration is achieved by correlating predictive capabilities of the simulation with experimental data, thus enhancing the parameter of the model towards achieving greater reliability for critical issues such as melt flow, heat transfer, and defect formation. It brings about an effective iteration so that the simulation will be able to accurately predict the behavior of the system under various conditions of casting.

With calibration, the simulation is applied in optimizing thermal die cycling. Thermal cycling is the biggest variable determining whether a steady die temperature will be attained because it is considered central to the quality control of continuous castings. The simulation of temperature gradients inside a die during casting can be used in this regard in determining optimal cooling and heating parameters that will maintain the die at optimal operating conditions.

A stable state die temperature also minimizes thermal stresses and the cast components' dimensional accuracy and quality of surface. It equally minimizes the chance of defects such as hot spots and early wear in dies, and extends the tool life. Incorporation of experimental calibration with thermal optimization ensures higher quality castings are produced - with more developed mechanical properties and smaller variability in production.



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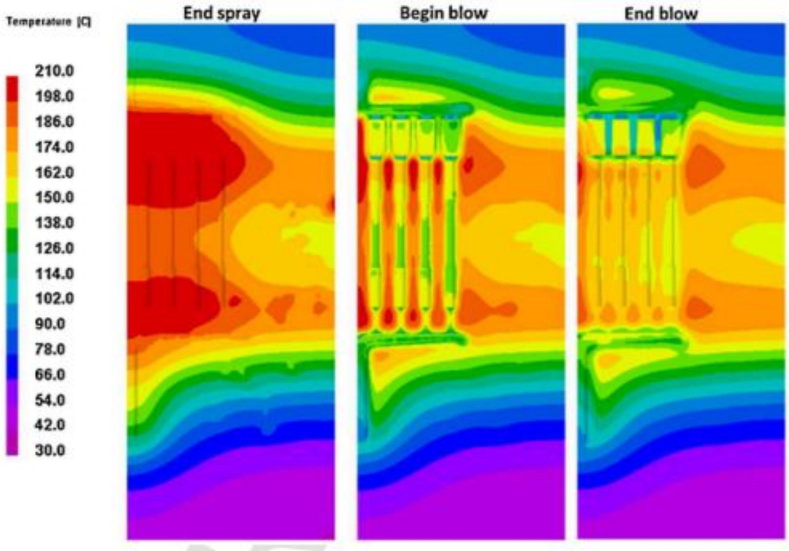

Figure 4: Simulation of the casting process

Analyzing for the Defects

High-Pressure Die Casting (HPDC) processes shall be analyzed in terms of defect formation, mainly related to porosity and entrapped air defects. These, being highly determinant for the cast component quality, generally occur due to improper flow dynamics, turbulence, and failure to vent properly during the injection stage. Therefore, optimization of casting parameters and improvements in piston shot profiles are recommended.

Correcting the shot profile requires monitoring the speed and injection pressure of the molten metal, making it gradually flow well into the mold cavity, hence reducing turbulence and the likelihood of air getting trapped within the casting. In addition, this research employs sophisticated simulation tools that can predict probable zones of defect within the casting, while also testing different configurations of parameters without trials on a physical model. This gives rise to prevention and addressing of factors that may lead to defect formation before the real production process.

All of these optimizations have brought out significant improvement in the mechanical properties of cast components, namely strength, ductility, and surface finish. Results thus obtained in this study are found to illustrate that strategic adjustments of process parameters combined with simulation-based defect analysis make it possible to produce high-quality castings with reduced defects. This approach not only enhances product performance but also reduces waste of material and costs of production.

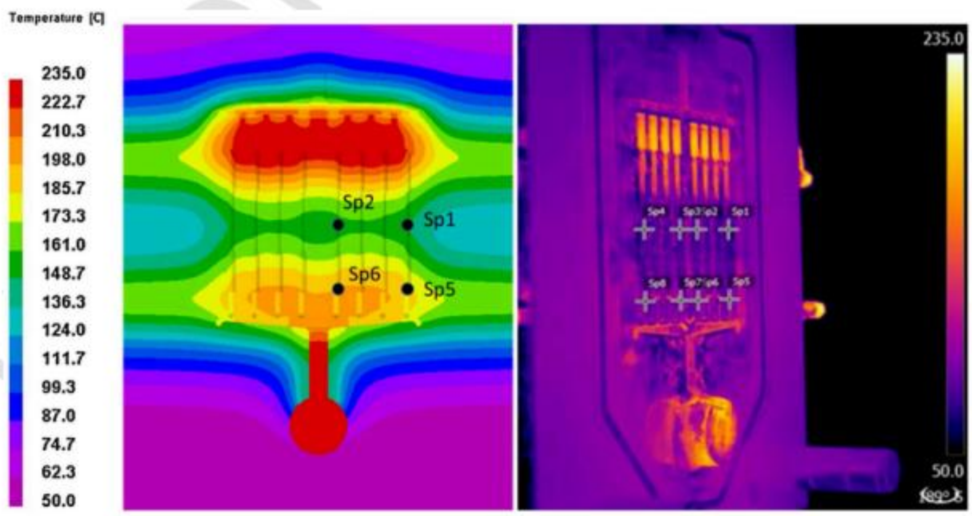

Figure 5: Analyzing the defects

IV. RESULTS AND DISCUSSION

Optimized piston profile:

It was found that an optimized piston slow shot acceleration position being at a 10 mm distance from the original position in combination with the slow shot speed of 0.4-0.6 ms^-1 significantly increased tensile properties of cast samples.

Improvement of Mechanical Properties

Inclusion of Al in the alloy led to increased ultimate tensile strength and elongation with altered shot profiles. Increases in tensile strength, however were associated with increased cooling rates at 400 L/h. Refinement of the microstructure to be dense and homogeneous led to improved mechanical qualities. Higher velocity shots improved mechanical stability and reliability of cast products through reduction in oxide segregation and trapped air. Reduction in pore size and homogeneity of eutectic silicon particles further improved the performance of the material.

Process Parameter Optimization

Acceptable parameters drawn from the simulations are: the injection speed will be 5 m/s; pouring temperature at 680°C; and mold temperature of 200°C. Shrinkage porosity increased and peaked at 140 seconds with increases in pressure holding times. Adjustments in the sequence of solidification reduced errors in parts with thick walls; in the meantime, well-designed cooling systems decrease residual stresses and shrinkage problems.

Neglect of Long-term Effects

The work is focused on direct mechanical properties like yield strength and ultimate tensile strength. Long-term performance and especially durability are ignored in the case of the castings, which is all the more important for practical applications.

Focus on Specific Materials

The main focus of this study was Al-Si alloys for the HPDC process. The limitation imposed by this would be the practical applicability of this to other materials or alloys that would yield different effects under similar conditions of casting.

Lack of real-world validation

Advanced algorithms of simulation predict casting behavior and defects, but till now, the correctness of all these algorithms could not be verified using actual experiments. Therefore, field data and experimental comparisons should be done effectively to ensure dependability and adaptability between theoretical models and industrial practices in order to attain good casting results.

V. CONCLUSION

New developments in simulation techniques and optimization strategies have revamped all forms of metal casting, including High-Pressure Die Casting, Low-Pressure Die Casting, and gravity casting. Once producers gain knowledge of various types of casting processes combined with optimized parameters, they get a chance to enhance the quality of the product, efficiency, and resource utilization. In HPDC, optimal parameters such as piston velocity profiles and thermal cycling directly influence the quality of casting. Increased slow shot velocities and optimized piston profiles have reduced oxide formation, improved tensile properties, and caused uniform oxide distribution. These changes are accompanied by porosity and air entrapment. Such changes need to take place in making structurally sound components, especially in alloys such as A356. In addition, changes in the gating design, where the lengths of runners are reduced, have speeded up mold filling while maintaining the mechanical properties of the castings, thus saving material and increasing utilisation of liquid metal.

Simulation-driven optimizations have also assisted in improving the LPDC process. Pressure holding times and cooling processes greatly influence casting quality, and studies have been shown to demonstrate improvements in mechanical properties due to microstructural refinement stemming from optimized cooling rates-that is, enhanced tensile strength for components such as wheel hubs. Such refinements thus illustrate how simulation integration into the design and production pipeline reduces the traditionally associated trial-and-error experimentation to expedite the concept-to-production process.

In gravity casting, feeders have been successfully applied to prevent shrinkage holes, hence demonstrating the capability of this process for compressor casings and other parts. However, centrifugal rotation has only limited ability in dealing with concentrated defects, and the choice of casting process for a particular application is still very crucial. Better gating systems and optimized cooling in gravity casting have further helped in making defect-free production that meets both mechanical and aesthetic criteria.

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