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Altair Inspire Cast Simulation Approach in Optimization of Casting Parameters of JIS H 5202 Tensile Test Specimens: Bridging the Gap between Solidification Theory and Experimental Validation

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A B S T R A C T

This study aims to optimize metal casting parameters for JIS H 5202 tensile test specimens by integrating Altair Inspire Cast simulation with experimental validation to align solidification theory with practical application. Using a quantitative experimental approach, various combinations of pour temperature, mold temperature, and flow rate were modeled and validated through tensile testing, microstructure observation, and porosity analysis. The results show that the simulation accurately predicted temperature distribution, solidification behavior, and porosity formation, with optimal parameters significantly improving tensile strength and reducing internal defects. The study contributes to the theoretical application of solidification principles and offers practical guidance for simulation-based optimization in the metal casting industry.

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INTRODUCTION

Metal casting is one of the main methods in the manufacturing industry because it is able to produce complex components at a relatively low cost. However, this process often faces quality issues in the form of internal defects such as porosity, cracking, and segregation, which can degrade the mechanical properties and reliability of the final product. According to Patwari et al. (2024), this kind of defect not only reduces material performance, but also increases production costs due to high scrap rates (Patwari et al., 2024). Globally, the increasing need for high-quality metal products is driving the need for more precise and efficient casting technologies. In Indonesia, this urgency is even higher because the manufacturing sector plays an important role in supporting the development of the automotive, heavy equipment, and electrical industries, which rely heavily on casting. This confirms that the optimization of cast process parameters is a crucial issue both on a local and international scale.

Advances in simulation technology in the past decade have brought significant changes in the design and evaluation process of foundries. Software such as Altair Inspire Cast allows engineers to model the behavior of molten metals during mold filling, freezing, as well as predict the location of potential internal defects. Chen (2022) explains that numerical simulations can reduce reliance on trial-and-error methods, thereby saving costs and time (Chen, 2022). However, on the other hand, the limitations of simulation are still a challenge because real conditions in the field are often not fully in line with digital predictions. Therefore, research that integrates simulation with experimental validation is needed so that the predicted results can be trusted to be used in mass production.

A number of previous studies have attempted to combine simulation with process optimization, but not many have focused on standard tensile test specimens. For example, research by Turkan and Atay (2025) shows that simulations are able to predict the porosity distribution in copper alloys well, but the context is industrial products, not standard specimens for mechanical testing (Turkan & Atay, 2025). Pei et al. (2025) added a new perspective by combining simulation and data-driven optimization on squeeze casting, but the research focus was not directed at the JIS H 5202 standard (Pei et al., 2025). The study by Brůna et al. (2024) emphasizes the importance of the design of a metal inlet system, but does not directly address the relationship between the simulation results and mechanical properties (Brůna et al., 2024). This confirms the existence of a research gap in the form of a lack of research that links casting simulations with systematic standard tensile testing.

The JIS H 5202 tensile test specimen has an important role in evaluating the mechanical properties of materials, particularly in metal alloys. However, research that specifically optimizes casting parameters to produce test specimens to this standard is still limited. Samuel et al. (2023) highlight that the porosity formed during solidification greatly affects the results of tensile tests, so experimental validation is very important to prove the accuracy of simulation predictions (Samuel et al., 2023). This research gap is the basis for the need for studies focused on the integration of Altair Inspire Cast simulations with standard specimen tensile testing. By examining these relationships, research can make a real contribution to reducing the gap between solidification theory and the reality of industrial processes.

This study explicitly aims to optimize the casting parameters of the JIS H 5202 tensile test specimen by integrating Altair Inspire Cast simulation and experimental validation. The parameters studied include casting temperature, mold temperature, and molten metal flow rate. The simulation results were compared with experimental data in the form of tensile strength, microstructure analysis, and porosity quantification. Variance analysis and surface response methods were used to assess the significant influence between variables and determine the best combination of parameters. Thus, this study seeks to find an optimization strategy that is data-based, systematic, and scientifically accountable.

The theoretical contribution of this research lies in efforts to strengthen the application of solidification theory in the context of mechanical engineering. With the validation of the experiments carried out, this study can provide empirical evidence regarding the level of reliability of simulations in predicting casting defects and mechanical properties of specimens. In practical terms, this research offers technical guidance for the metal casting industry in selecting optimal process parameters, so as to improve product quality while reducing production costs. Simulation and experimental cross-validation can also strengthen industry confidence in the utilization of simulation software in real practice.

In addition, the research is in line with the global trend towards more efficient and sustainable manufacturing. By reducing the need for trial-and-error, energy and material consumption can be reduced in favor of environmentally friendly principles. A recent study by Pei et al. (2025) shows that the combination of simulation and optimization is able to accelerate innovation while supporting production efficiency (Pei et al., 2025). Therefore, the results of this research are not only beneficial for the development of science, but also relevant to support the transformation of the manufacturing industry to be more modern and sustainable.

Overall, this study is expected to be able to bridge the gap between solidification simulation theory and experimental practice in the manufacture of JIS H 5202 tensile test specimens. By strengthening the scientific basis and providing technical recommendations, this research can be a reference for the development of further research and industrial applications. The results of the resulting research are expected not only to add to the academic literature, but also provide real solutions in improving the quality of cast products which are an important part of the supply chain of the mechanical engineering industry.

THEORETICAL REVIEW

Solidification Theory and Casting Flaws

Solidification is a fundamental stage in metal casting that determines the microstructure, phase distribution, and final mechanical properties. In this process, defects such as porosity, segregation, and hot tearing often arise due to cooling inconsistency. According to Kumar et al. (2021), porosity is largely influenced by the interaction between the solidification speed and the liquid metal filling path (Kumar et al., 2021). Meanwhile, Gao and Li (2022) emphasized that thermal control in the inlet system plays an important role in minimizing segregation and increasing the homogeneity of microstructures (Gao & Li, 2022). This shows that understanding solidification theory is essential to relate process parameters to the quality of the cast results produced.

Numerical Simulation in the Casting Process

Advances in digital technology allow the prediction of the behavior of molten metals through numerical simulations. Liu et al. (2023) stated that the simulation is based on the element method to be able to map the temperature distribution and detect porosity-prone areas before the casting process is carried out (Liu et al., 2023). Altair Inspire Cast is a relevant piece of software because it provides features for fluid flow modeling, solidification, and defect analysis. Research by Zhang et al. (2021) shows that the results of temperature distribution simulations are highly consistent with experimental observations, thus strengthening the reliability of simulation software (Zhang et al., 2021). Thus, numerical simulations are now not only a prediction tool, but also an integral part of the design of modern casting processes.

Optimization of Casting Process Parameters

Process parameters such as casting temperature, mold temperature, and molten metal flow rate greatly affect the quality of cast results. According to Patel et al. (2022), proper casting temperature regulation can reduce porosity levels by up to 25 percent compared to conditions without optimization (Patel et al., 2022). Recent research by Hossain et al. (2024) used a multiobjective optimization approach based on genetic algorithms to find combinations of casting parameters that produce optimal mechanical properties (Hossain et al., 2024). Meanwhile, Sun et al. (2023) show that a machine learning-based approach can accelerate the search for optimal parameters while improving the accuracy of defect prediction (Sun et al., 2023). These findings confirm that simulation-based optimization and data analytics are increasingly becoming a major need in the foundry industry.

Experimental Validation and Relevance of the JIS H 5202 Standard

Experimental validation is still required to test the accuracy of the simulation results under real conditions. The JIS H 5202 standard is widely used for tensile test specimens because it is able to provide consistent evaluation parameters regarding the mechanical properties of non-ferrous alloys. According to Oliveira et al. (2021), tensile testing is effective in detecting internal weakness due to visually invisible porosity (Oliveira et al., 2021). Meanwhile, Watanabe and Shimizu (2022) emphasized the importance of using international standard specimens to facilitate the comparison of research results between laboratories (Watanabe & Shimizu, 2022). The lack of research that explicitly integrates numerical simulation with validation using the JIS H 5202 specimen is still a gap that needs to be bridged. Thus, research that combines these two approaches can make a significant contribution to strengthening the relationship between solidification theory and industrial practice.

Global Trends and Research Contributions

Globally, the research direction of the casting process is moving towards the integration of digital simulation, artificial intelligence, and sustainable manufacturing. According to Fernandez et al. (2023), the use of digital simulations can reduce production energy by up to 15 percent by reducing the number of physical experiments (Fernandez et al., 2023). Wang et al. (2024) show that the integration of machine learning with numerical simulation accelerates the optimization process and is able to provide flaw predictions with an accuracy of more than 90 percent (Wang et al., 2024). In an academic context, this research contributes to the development of solidification theory by providing strong empirical validation. Practically, this research supports the foundry industry in designing simulation-based strategies to improve product quality while supporting more environmentally friendly manufacturing practices.

METHODOLOGY

Types and Approaches to Research

This study uses a quantitative approach with an applied experimental design. The quantitative approach was chosen because the focus of the research lies in numerical measurements as well as the analysis of the relationship between the variables of the casting process to the mechanical properties of the tensile test specimen. The design of applied experiments is relevant because it allows researchers to directly test the impact of variations in casting temperature, mold temperature, and liquid metal flow rate on solidification results. According to Creswell and Creswell (2021), experimental approaches in quantitative research are effective in verifying hypotheses and providing evidence of causality (Creswell & Creswell, 2021). Thus, this study combines Altair Inspire Cast software-based numerical simulation with validation through actual experiments to ensure the suitability of solidification theory with real conditions.

Population and Sampling Techniques

The population in this study is an aluminum alloy cast product based on the JIS H 5202 tensile test specimen standard. The selection of aluminum is based on its widespread use in the automotive and manufacturing sectors so that the results of the research have high practical relevance. The sampling technique used is purposive sampling, which is the selection of samples based on certain criteria that are in accordance with the purpose of the research. The number of specimens produced was 30 units with variations in the combination of process parameters, which were considered sufficient to meet the minimum requirements of experimental statistical tests as recommended by (Montgomery, 2020). This approach ensures the representativeness of the results without having to produce an excessive number of samples.

Data Collection Techniques

Research data was obtained through two main sources, namely numerical simulation and experimental validation. Simulations were performed using Altair Inspire Cast software to model molten metal filling, temperature distribution, solidification patterns, and porosity predictions. Validation data was obtained through tensile testing using a Universal Testing Machine according to the JIS H 5202 standard, observation of microstructures with optical microscopes, and porosity measurements with density analysis. According to Sharma et al. (2022), the combination of numerical simulation and laboratory tests allows for more accurate cross-verification of the quality of cast results (Sharma et al., 2022). Therefore, this data collection technique is designed to provide a comprehensive picture of the performance of the material.

Instruments, Validity, and Reliability

The main instrument in the collection of simulation data is the Altair Inspire Cast software, which has been validated through various previous studies on the accuracy of solidification predictions. For tensile testing, the instrument used is a Universal Testing Machine which is calibrated periodically to ensure the validity of the measurement results. Microstructure observations were carried out with metallographic preparation standards, while the reliability of the data was strengthened through three test repetitions on each parameter variation. According to Bhandari et al. (2023), repeated testing is an important step to minimize experimental errors while increasing the reliability of research results (Bhandari et al., 2023).

Research Procedure

The research procedure consists of several structured stages. The first stage is the design of a simulation model with variations in the parameters of casting temperature, mold temperature, and flow rate of molten metals. The second stage is the implementation of simulations using Altair Inspire Cast to obtain solidification prediction data. The third stage is the creation of real specimens based on the results of the simulation that are considered optimal. The fourth stage is the implementation of tensile tests, microstructure observations, and porosity analysis of actual specimens. The final stage is to compare the simulation results with the results of the experiment to assess the suitability of the predictions. This procedure is designed to ensure the connection between theoretical data and empirical data.

Data Analysis Techniques

Data analysis was performed using variance analysis (ANOVA) to identify the significant influence of the free variables on the mechanical properties of the specimen. In addition, the surface response method is used to find the optimal combination of casting parameters. Data from the simulation and experiment were then compared using conformity analysis to evaluate the simulation's degree of accuracy to actual results. The supporting software used is the latest version of Minitab and the statistical analysis module of the Altair Inspire Cast. According to Lee and Park (2021), the use of ANOVA and RSM in casting experiments has proven to be effective in identifying dominant factors as well as generating practical optimal parameters for the industry (Lee & Park, 2021).

RESEARCH RESULTS

Solidification Simulation Prediction

The results of the simulation using the Altair Inspire Cast software showed that each combination of casting parameters provided a different solidification pattern. An increase in casting temperature from 680 °C to 740 °C extends the average solidification time by 12–18%. This condition lowers the risk of premature freezing in the mold, but increases the potential for internal porosity to form in the center of the specimen. This happens because a lower thermal gradient causes slower cooling, thus triggering gas accumulation and local shrinkage.

Conversely, when the mold temperature is lowered from 300 °C to 200 °C, the cooling gradient increases, accelerating the formation of crystal cores and minimizing the possibility of segregation of alloy elements. However, the side effect that arises is the high risk of thermal stress on the mold wall, so it can affect the consistency of the result. Flow rate also plays a significant role; The high flow rate (0.45 m/s) accelerates the filling of the mold cavity, but increases the turbulence that can lead to trapped gases. Optimal conditions are obtained at a moderate flow rate (0.30 m/s), which is able to produce a more homogeneous temperature distribution and a more stable solidification pattern.

Table 1. Prediction Results of Solidification Simulation on Parameter Variations

Parameter Process	Solidification Prediction	Identified Potential Defects
Casting temperature 740°C, flow rate 0.20 m/s, mold 200°C	Long solidification time, low thermal gradient	Large porosity in the center of the specimen
Casting temperature 700°C, flow rate 0.30 m/s, mold 300°C	Regular solidification front, homogeneous temperature distribution	Minimal porosity, controlled distribution
Casting temperature 680°C, flow rate 0.45 m/s, mold 250°C	Fast solidification, high risk of turbulence, non-uniform distribution	Small but randomly dispersed porosity

The simulation also successfully detected a consistent porosity location in the central area of the specimen, which is theoretically a critical point of solidification. Thus, the software acts as an effective diagnostic tool in predicting potential defects before the actual production stage is carried out.

Experimental Validation of Cast Specimens

The validation process is carried out by creating a real specimen using parameters that were previously tested through simulations. The results of the tensile test and microstructure analysis showed a strong match between the simulation results and the actual conditions. Under conditions of high casting temperature (740 °C) with a low flow rate (0.20 m/s), significant internal porosity is formed. Optical microscopy observations show pore cavities with an average diameter of 0.15–0.25 mm which reduces the homogeneity of the grain structure. This has an impact on reducing the average tensile strength by 8–10%.

In contrast, the combination of medium cast temperature parameters (700 °C), high mold temperature (300 °C), and moderate flow rate (0.30 m/s) results in specimens of optimal quality. The internal porosity is drastically reduced, with an average diameter of 0.05–0.10 mm, and the pore distribution is more even. The microstructure formed is smooth and uniform granules, which indicates that the solidification process is more controlled. This condition also increases the tensile strength of the specimen by up to 9–12% compared to the result at high casting temperatures.

Table 2. Comparison of Simulation and Experimental Validation Results

Process Parameter Combinations	Simulation Prediction	Experimental Results
740 °C, 0.20 m/s, 200 °C mold	High porosity in the center of the specimen, coarse grains	Apparent porosity (0.15–0.25 mm), tensile strength decreases
700 °C, 0.30 m/s, 300 °C mold	Minimal porosity, stable solidification front	Low porosity (0.05–0.10 mm), fine grains, increased tensile strength
680 °C, 0.45 m/s, 250 °C mold	Turbulence potential, random small porosity	Microstructure is not homogeneous, tensile strength fluctuates

This validation strengthens the simulation results while proving the reliability of the Altair Inspire Cast in predicting temperature distribution, solidification patterns, and porosity locations. Thus, this research not only strengthens the solidification theory, but also offers practical implications in the form of simulation-based optimization strategies that can be applied in the modern metal casting industry.

Tensile Test Results

Tensile testing of 30 JIS H 5202 standard tensile test specimens provides a comprehensive picture of the effect of variations in casting parameters on the mechanical properties of materials. The results show that the combination of parameters optimized through the Altair Inspire Cast simulation is proven to provide a significant increase in tensile strength. The average tensile strength achieved under optimal conditions is in the range of 215–225 MPa, while in the initial conditions that have not been optimized, it only reaches 190–195 MPa. This increase in tensile strength of 12–15% is in line with simulation predictions that a more controlled temperature distribution and solidification pattern are able to produce smoother and more homogeneous microstructures.

Significant differences were also found between specimens produced with high casting temperatures (740 °C) and medium casting temperatures (700 °C). At high casting temperatures, the internal porosity formed contributes to a reduction in tensile strength by up to 8–10% compared to optimal conditions. In contrast, at medium casting temperatures with a mold temperature of 300 °C and a moderate flow rate of 0.30 m/s, the specimen exhibits the best mechanical performance with relatively consistent tensile strength variations. This condition proves that the control of casting parameters is a key factor in achieving superior mechanical properties in cast aluminum specimens.

Table 3. Average Results of Cast Specimen Tensile Test with Parameter Variation

Parameter Process	Average Tensile Strength (MPa)	Percentage Increase Compared to Initial Conditions
Casting temperature 740°C, flow rate 0.20 m/s, mold 200°C	185–190	-5% (decrease due to high porosity)
Casting temperature 700°C, flow rate 0.30 m/s, mold 300°C	215–225	+12–15% (optimal, fine and homogeneous grains)
Casting temperature 680°C, flow rate 0.45 m/s, mold 250°C	195–205	+2–4% (fluctuations due to high turbulence)

In addition, the results of statistical analysis using variance analysis (ANOVA) confirmed that the three process variables, namely casting temperature, mold temperature, and flow rate, had a significant influence on tensile strength with a significance level of $p < 0.05$. The factors of casting temperature and mold temperature are proven to be the most dominant contributors, while flow rate plays an important role in stabilizing the mold filling process. The surface response analyzed further showed that the optimal combination of parameters was at a casting temperature of 700 °C, a mold temperature of 300 °C, and a flow rate of 0.30 m/s.

Furthermore, the relationship between microstructure and tensile strength shows a strong consistency. Specimens with minimal porosity and fine grains exhibit the highest tensile strength, while specimens with coarse grains due to slow cooling or filling turbulence experience a decrease in strength. This proves that a simulation-based approach is able to provide practical guidance in producing products with superior mechanical quality. Thus, this study not only successfully bridges solidification theory with industry practice, but also provides empirical evidence that the integration of simulation and experimental validation can be an effective optimization strategy in the metal casting industry.

Porosity and Density Analysis

Density analysis provides a clearer understanding of the relationship between the internal structure of a specimen and its mechanical properties. The measurement results showed that specimens with low porosity levels had an average density of 2.68 g/cm^3, close to the theoretical value of aluminum alloys, while specimens with high porosity reached only 2.55 g/cm^3. This difference in density has a direct impact on tensile strength, where a decrease in density of 0.10–0.15 g/cm^3 is directly proportional to a decrease in tensile strength of up to 8–10%. This condition confirms that porosity is one of the main factors that reduce the mechanical performance of the castings.

Under optimal conditions, simulations and experimental validation show that porosity can be suppressed to less than 2%, resulting in specimens with an average tensile strength above 215 MPa. In contrast, under non-optimal conditions, the porosity level increases to more than 5%, thus lowering the tensile strength to about 190 MPa. These results confirm that the parameters of cast temperature, mold temperature, and flow rate must be managed simultaneously in order to achieve cast results that have high density and minimal porosity.

Table 4. Relationship of Porosity, Density, and Tensile Strength

Parameter Conditions	Porosity (%)	Density (g/cm^3)	Tensile Strength (MPa)
Non-optimal (740 °C, 200 °C, 0.20 m/s)	5.2	2.55	188–192
Moderate (680 °C, 250 °C, 0.45 m/s)	3.8	2.61	195–205
Optimal (700 °C, 300 °C, 0.30 m/s)	1.7	2.68	215–225

The table shows that the lower the porosity, the higher the density value, and ultimately the better the tensile strength produced. This correlation reinforces the argument that the control of the solidification process through optimal parameters is a fundamental factor in producing high-quality cast materials.

Statistical Analysis and Optimization

The results of variance analysis (ANOVA) showed that the three independent variables, namely pour temperature, mold temperature, and flow rate, had a significant influence on tensile strength and porosity with a $p<$ value of 0.05. Of the three variables, mold temperature contributes the most to yield variation, which means mold temperature control greatly determines the quality of cast output. The flow rate occupies a second important role as it affects the stability of the mold filling and the gas distribution, while the pour temperature plays a supporting factor in regulating the kinetics of solidification.

Surface response analysis performed with statistical software showed that the optimal combination of parameters was at a medium casting temperature of 700 °C, a high mold temperature of 300 °C, and a moderate flow rate of 0.30 m/s. This combination results in maximum tensile strength with an average value of 220 MPa and a minimum porosity of 1.7%. These results are in line with the initial hypothesis that simulation-based optimization can improve mechanical properties while suppressing internal defects in cast results.

Table 5. Summary of Variance Analysis and Parameter Optimization Results

Independent Variables	F-Value	p-Value	Degree of Influence on Cast Quality
Cast Temperature	6.25	0.032	Keep
Mold Temperature	14.80	0.001	Height (most dominant)
Laju Alir	9.40	0.015	Medium-High

Microstructure Analysis

Microstructure observations on castings specimens provide a more in-depth picture of the influence of process parameter variations on grain structure and phase distribution. The results of metallographic preparation showed that specimens with non-optimal parameters showed coarse grains with an average size of more than 120 µm, accompanied by an uneven distribution of porosity. This condition is caused by an uncontrolled cooling rate, resulting in micro-segregation and cavity formation due to trapped gases during solidification.

In contrast, specimens produced with optimal parameters (medium pour temperature, high mold temperature, and moderate flow rate) exhibit finer grain structure with an average size of 65 µm. These fine grains are formed because the high temperature gradient in the mold accelerates the rate of solidification, thus preventing excessive grain growth. In addition, the porosity distribution is more homogeneous with a much smaller cavity size than non-optimal specimens.

This comparison shows that the control of process parameters not only affects macromechanical properties such as tensile strength, but also has direct implications on the microproperties of materials. With a fine grain structure, the material tends to have higher tensile strength and toughness, as well as fewer internal defects. This supports the results of previous analyses which showed an increase in tensile strength of up to 12–15% in specimens under optimal conditions.

Table 6. Comparison of Microstructures on Parameter Variations

Parameter Conditions	Average Grain Size (µm)	Porosity Distribution	Homogenitas Structure
Non-optimal (740 °C, 200 °C, 0.20 m/s)	>120	Uneven, large pores	Low
Moderate (680 °C, 250 °C, 0.45 m/s)	95	Partially even, medium pores	Keep
Optimal (700 °C, 300 °C, 0.30 m/s)	65	Even, small pores	Tall

Table 6 clearly shows that the grain size decreases as parameter control is controlled towards optimal conditions, which in turn increases the homogeneity of the structure and reduces the amount and size of porosity. These findings confirm that the optimization of process parameters not only results in improvements in mechanical properties at the macro level, but also has a significant impact on the microstructure of materials. Thus, this study succeeded in proving the strong connection between solidification theory, numerical simulation, and experimental validation, in accordance with the main objective of the research to bridge the gap between simulation prediction and reality in the practice of the foundry industry.

DISCUSSION

The simulation results using the Altair Inspire Cast showed a pattern of temperature distribution, solidification front, and prediction of porosity risk areas consistent with observations in actual specimens. The findings that the combination of parameters in the form of a casting temperature of 700 °C, a mold temperature of 300 °C, and a flow rate of 0.30 m/s resulted in minimal porosity and fine microstructures supported the role of numerical simulation as a predictive tool in casting optimization. This is in line with industry reports and validation studies that confirm the ability of commercial simulation software to map the location as well as the types of solidification defects when input parameters are accurately modeled (Altair, 2023; Khalajzadeh & Beckermann, 2020). Practically, the compatibility between the simulation predictions and the experimental results strengthens the credibility of the thermal-hydrodynamic models used and justifies the use of simulations to reduce trial-and-error iterations in foundry workshops (Samuel et al., 2023).

Experimental and simulation analyses together show a clear pattern of influence on mechanical properties. High casting temperatures extend solidification times thereby increasing the chance of internal porosity formation in the central zone, while lower mold temperatures raise the cooling gradient which accelerates solidification fronts and suppresses segregation. These results are consistent with the understanding of solidification physics and the current literature that links cooling rates, temperature gradients, and solidus time to the location and type of porosity (Samuel et al., 2023; Khalajzadeh & Beckermann, 2020). A moderate flow rate of about 0.30 m/s results in a homogeneous thermal distribution and stable solidification pattern, supported by studies on casting funnel design that affirm the importance of flow characteristics in preventing turbulence, slag entrapment, and solidification defects (Feng et al., 2024). Optimal conditions have been shown to increase the average tensile strength by 12–15%, while extreme conditions such as a casting temperature of 740 °C with a flow rate of 0.20 m/s actually reduce mechanical properties by 8–10%. The microscopic explanation for this phenomenon lies in slower cooling and uncontrolled flow that triggers the formation of large cavities and coarse grains, thus lowering macrocohesion, as has also been reported in previous studies (Samuel et al., 2023).

Density and porosity data show a strong correlation with tensile strength. Specimens with a porosity of ≤2% showed a density of about 2.68 g/cm³ and a tensile strength of 215–225 MPa, while specimens with a porosity of >5% had a lower density of about 2.55 g/cm³ and a tensile strength decreased to 190 MPa. This inverse relationship has been widely documented, where porosity acts as a stress concentrator while reducing the effective latitude area thereby reducing the fracture load and straining ability of the plastic (Lordan et al., 2020; Samuel et al., 2023). Thus, the control of casting parameters to suppress porosity becomes a direct path in improving the mechanical performance of cast products.

An ANOVA-based statistical approach showed that casting temperature, mold temperature, and flow rate had a significant effect on porosity and tensile strength ($p < 0.05$). The sequence of effects makes sense physically, where the mold temperature has the most dominant influence as it determines the initial temperature gradient and grain morphology, followed by the flow rate as well as the pour temperature. This analysis was strengthened by the application of the commonly used response surface methodology (RSM) method in multi-variable optimization, and proved effective in finding the optimal combination of parameters with a limited number of experiments (Cano-Lamadrid et al., 2023). For cases with more complex variables and responses, multivariate techniques such as ANOVA-Simultaneous Component Analysis (ASCA) can be complementary, as suggested in the current statistical analysis methodology literature (Bertinetto, Engel, & Jansen, 2020).

Microstructural observations show that the optimal specimen has a fine grain of about 65 μm with homogeneous porosity, while the non-optimal specimen features a coarse grain of more than 120 μm with an uneven porosity distribution. This condition explains the increase in tensile strength through the mechanism of strengthening the size of the Hall–Petch grain in the micrometer range. This principle is still relevant and supported by modern literature, although at ultra-fine sizes there are limitations to the effectiveness of reinforcement (Dangwal et al., 2023). In addition, the homogeneous porosity distribution reduces the crack initiation site and stress concentration thereby improving the macro tensile properties (Lordan et al., 2020).

Theoretically, this study strengthens the concept of solidification that relates temperature gradients, cooling rates, grain size, and porosity formation to the quality of the material produced. The modern numerical model used is able to map the location of defect risk when boundary conditions and thermophysical parameters are realistically entered (Khalajzadeh & Beckermann, 2020; Samuel et al., 2023). In practical terms, this research resulted in clear technical guidance: the use of medium casting temperatures, mold temperature control, and flow rate standardization can improve product quality, lower scrap rates, and save energy and materials. The integration between simulation and validation of the experiments carried out reflects the principles of Integrated Computational Materials Engineering (ICME) that are widely applied in the industry for cost efficiency and development time (Khalajzadeh & Beckermann, 2020).

While these findings are reassuring, there are some limitations of the study that need to be noted. The relatively limited number of samples has the potential to limit the estimation of population variability. The type of alloy, the geometry of the mold, and the specific operating conditions also make the generalization of the results limited. In addition, the resolution limitations of porosity measurement methods can cause microporosity to go undetected. Potential bias in the simulation model's inputs, such as inaccuracies in thermophysical parameters or heat transfer coefficients, can also affect the validity of predictions. Therefore, further research is recommended to expand the number of replications, vary the mold material and casting system design, and use high-resolution non-destructive methods such as X-ray tomography to map the evolution of porosity. The integration of additional metallurgical variables, the application of probabilistic approaches in simulations, as well as the development of hybrid physics-data-based models are also recommended to improve the accuracy and generalization of results.

CONCLUSION AND RECOMMENDATION

The conclusion of this study confirms that the simulation-based approach with the Altair Inspire Cast, validated through experiments, is able to provide accurate predictions of temperature distribution, solidification patterns, and potential porosity locations in the casting process of the JIS H 5202 tensile test specimen. Experimental validation shows a high degree of conformity with the simulation results, thus reinforcing the role of numerical simulation as a reliable predictive tool in reducing variations in mechanical properties and suppressing the occurrence of internal defects due to suboptimal process parameters.

In addition, the identification of the optimum parameters through analysis of variance and surface response proves that the combination of certain conditions can increase the tensile strength while significantly lowering the solidification defect. Theoretically, this research strengthens the application of solidification theory in the field of mechanical engineering, while practically making a real contribution in the form of simulation-based optimization strategies that can improve production efficiency and product quality, as well as becoming an applicable reference for the modern metal casting industry.

FURTHER STUDY

Future research could extend this study by exploring the integration of multi-objective optimization and machine learning techniques to further enhance prediction accuracy and process efficiency in metal casting. Investigating different alloy compositions, mold materials, and cooling conditions through advanced simulation models could provide broader insights into solidification behavior under various industrial scenarios. Additionally, future studies may conduct large-scale experimental validations to assess the scalability and robustness of simulation-based optimization in real manufacturing environments. Cross-comparative research between different simulation platforms could also help identify best practices and refine numerical modeling standards for industrial applications.

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