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Design and Simulation of a Maintenance-friendly and Cost-effective Molten Aluminum Alloy Casting Mechanism

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The aim of this research was to design and simulate a low-cost, easy-to-maintain molten aluminum alloy casting mechanism. This mechanism was intended to address labor shortages in harsh and high-temperature environments. The functional requirements of the mechanism were as follows: it needed to withstand temperatures exceeding 700 ℃, operate without deformation, and ensure that the ladle's positioning error during each rotation did not exceed 1 deg. Additionally, the mechanism's durability had to meet industry standards, with the ladle's output shaft capable of bearing pressures exceeding 100 kg/cm^2. The design should be modular, allowing for the replacement of specific components to accommodate varying specifications in the future. To begin with, a 3D model was constructed using SolidWorks CAD software to verify operational interferences and simulate assembly, ensuring that the design was practical and logically sound. During the design process, mechanical design handbooks and catalogs from major component suppliers were consulted to utilize standard sizes and specifications as much as possible. Once the model was confirmed, structural analyses were conducted using Ansys to ensure that the mechanism could withstand significant loads without failure. Furthermore, the design would focus on ensuring that the mechanism was robust and reliable under high-temperature conditions, reducing the need for frequent maintenance and downtime. The modular design approach not only enhances the flexibility of the mechanism but also simplifies future upgrades and adjustments, ensuring long-term usability and adaptability.

1. Introduction

The working environment in the foundry industry is characterized by high temperatures and high levels of dust, making the occurrence of workplace safety incidents more likely.

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Increasingly, businesses are introducing six-axis automated robotic arms to replace manual labor in such environments. This approach not only improves work efficiency but also enhances product stability. To address the challenges of high temperatures and high levels of dust during aluminum alloy casting, a six-axis automated robotic arm casting mechanism is introduced. This mechanism includes motors, reducers, transmission mechanisms, control interfaces, chain tensioning systems, and ladles for casting. The programmable path feature of the six-axis robotic arm enables flexible manufacturing, ensuring the precise control of the weight of the aluminum soup poured each time within a certain range, thus enhancing production efficiency. The aim of this study is to design a complete system applicable to all casting-related industries.(1–3) The modular design enhances flexibility in application, enabling rapid implementation on production lines to improve efficiency.

Embedding sensors in automated aluminum alloy casting mechanisms is crucial. These sensors provide real-time data to monitor and control the casting process, ensuring product quality and production efficiency. Common applications of sensors in the casting process include temperature, pressure, flow, displacement, quality, and humidity sensors. By integrating these sensors with control systems, the real-time monitoring and adjustment of the automated aluminum alloy casting process can be achieved, enhancing production efficiency and ensuring product quality. Fernandes de Souza *et al.* tackled the issue by integrating artificial neural network techniques, real data, and clustering methods to develop soft sensors for estimating temperature, metal level in aluminum reduction cells (pots), and aluminum fluoride percentage in the electrolytic bath.(4) Zhang *et al.* utilized two innovative fiber-optic sensors to monitor real-time mold gaps and thermal profiles during the solidification of A356 aluminum in a permanent mold casting.(5) The experimental configuration includes a custom-designed mold system constructed from uncoated and unheated tool steel, enabling the straightforward installation of fiber-optic sensors.(5)

Tayade *et al.* published a paper in 2014 entitled "PLC Based Hydraulic Auto Ladle System",(6) which discusses the research and design of a PLC-based hydraulic automatic ladle system for the production of aluminum components. The primary goal of this system is to enhance the accuracy and consistency of product quality by eliminating human errors during the aluminum pouring process through automation. In 2018, Momin and Patil published "Automatic Ladle Control with Job Database Using PLC-SCADA".(7) In this study, they introduced an automated ladle control system that integrates a job database using PLC-SCADA technology. The objectives of this system are to reduce human hazards, minimize pouring time, and decrease overflow losses, thereby achieving high-quality products. In 2018, Priya *et al.* published a paper entitled "Design and Simulation of a Robotic Manipulator for Ladle with PLC".(8) In this paper, they described in detail the design and simulation of a robotic manipulator for automated casting, which was also aimed at improving production efficiency and reducing human errors. In this study, they mentioned a preset metal melting point range of approximately 640–700 ℃, which is close to the aluminum melting point of 660 ℃ referenced in this research. Therefore, the preset temperature for this study was set to 700 ℃ to ensure optimal results.

From these studies, it is evident that there are two main approaches to creating an automated aluminum alloy casting mechanism. The first approach involves directly building the mechanism. While this method can ultimately produce a functioning system, it often requires significant time for system adjustments and refinements, and the final outcome may not be optimal. The second approach involves using simulation to design and test the entire mechanism before manufacturing. Heugenhausera *et al.* optimized the thermal conditions conducive to efficient melt flow.(9) Subsequently, they employed numerical simulation techniques, utilizing a commercial software package designed for fluid flow and solidification processes, to identify the most appropriate casting device for their study.(9) Bosse *et al.* employed physics-based simulations to extract essential insights into critical process conditions leading to defects and their specific characteristics.(10) Utilizing the superposition technique, they generated synthetic image data by overlaying real defect-free images with "simulated" defect image fragments. This innovative approach facilitated a detailed examination of defect formation and behavior under various conditions, providing valuable insights for process optimization and quality control.(10)

The simulation method allows for the optimization of parameters and the identification of potential issues in a virtual environment, resulting in a more efficient and effective final product once it is built. In this study, a 3D model was constructed using SolidWorks CAD software to verify operational interferences and simulate assembly. Then, the relative parameters of the materials used and the constructed model were incorporated into the finite element analysis software Ansys. Therefore, leveraging simulations can significantly enhance the design process, leading to higher performance and reduced development time for automated casting systems.

2. Simulation Process and Parameters

Upon determining the research objectives, in this study, we commenced the design of an automated mechanism for aluminum alloy casting. Literature pertaining to casting and automatic control was gathered to determine the necessary components based on functional requirements. Subsequently, various components were analyzed, and those meeting the requirements were selected. Factors affecting component selection include environmental temperature, cost, mechanical characteristics, and durability, among others. Using dimension drawings provided by manufacturers, we conducted 3D modeling in SolidWorks at a 1:1 scale to ensure no interference among components and no assembly dead ends. The mechanism's ability to rotate at desired angles was verified. Finally, the model underwent strength analysis in the finite element analysis software Ansys to confirm its overall compliance with expectations. In his study, the 3D modeling software Solidworks was utilized to create the overall mechanism. The aluminum alloy casting automation mechanism model established in this study was mainly divided into five major parts, which were, in sequence, the adapter assembly, the frame assembly, the bearing assembly, the lower support assembly, and the ladle.

The adapter assembly consisted of five components: one adapter plate and four connecting seats, primarily made of A6061 material. The main purpose of the adapter plate was to connect the overall mechanism to the fixed end. Its specifications were 150 × 150 mm^2 with a thickness of 20 mm. The plate featured a total of 26 holes, with 8 holes used for external fixation and the remaining holes used to secure the connecting seats. The connecting seats served the primary purpose of linking the adapter plate to the mechanism's frame. They were divided into two types: upper and lower. The upper connecting seats had dimensions of 56 × 52 × 56 mm^3 and included five holes on the sides and top for connecting to the frame, as well as four holes on the front for attaching to the adapter plate. The lower connecting seats measured 56 × 54 × 56 mm^3 and had five holes on the sides for frame connection and five holes on the front for connecting to the adapter plate.

The primary purpose of the frame assembly was to increase the overall length, preventing the upper part from being too close to the molten aluminum below, which could cause high-temperature damage, and to enhance overall stability. The main material used for the frame was SUS304 stainless steel. The frame was composed of two identical hollow stainless steel structures, each featuring several holes. The upper holes were used for connecting to the connecting seats, the middle holes for attaching the back plate, and the lower holes for connecting the side plates, base plate, and bearing seats. The bearing assembly consisted of bearings and a shaft. The bearings were made of ZrO_2, while the shaft was made of AISI304L. There were two bearings, each with an outer diameter of 42 mm and an inner diameter of 20 mm. ZrO_2 was chosen for its self-lubricating and heat-insulating properties, which prevented excessive heat transfer to the mechanism, and for its excellent strength, as shown in Fig. 1. The shaft had a diameter of 20 mm and a length of 220 mm and the front end featured a 10.2 mm through-hole for securing the shaft to the ladle, allowing for rotation. The shaft was also used to connect a chain, driven by a motor, to facilitate the automatic scooping and pouring of molten aluminum.

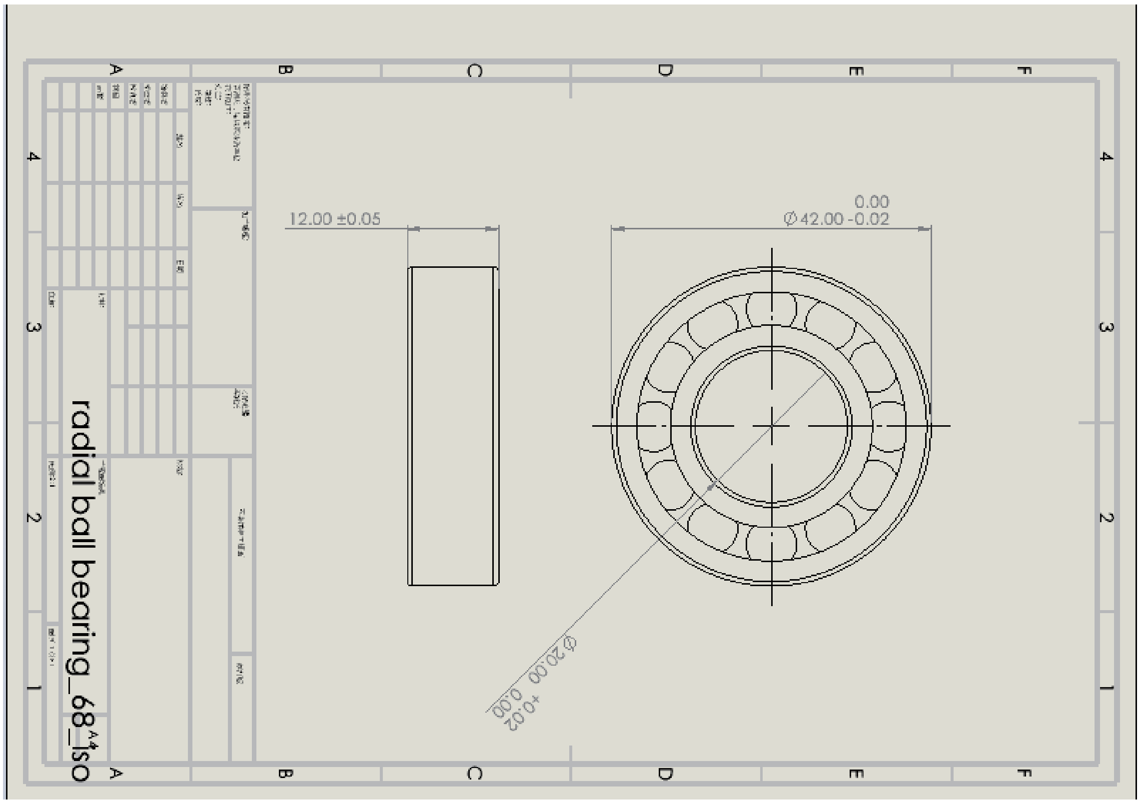
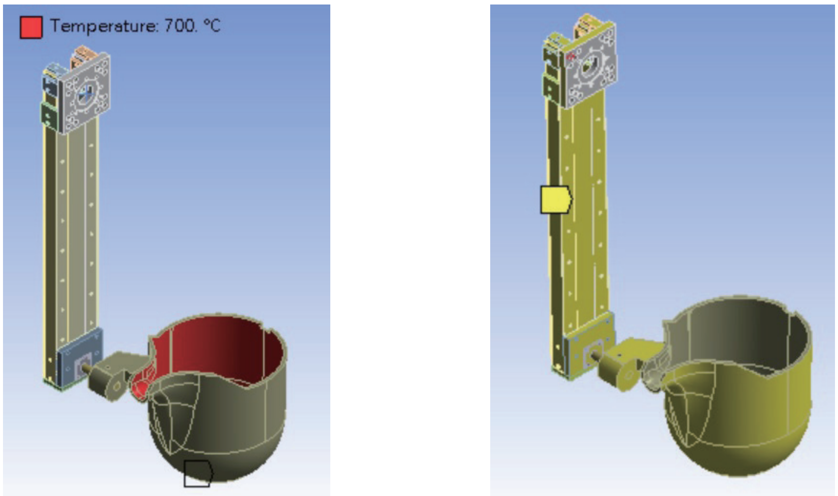


Fig. 1. (Color online) Diagram for bearing dimensions of the investigated molten aluminum alloy casting mechanism.

The lower support assembly primarily consisted of the bearing seat, base plate, side plates, and bearing cover, all made of SUS304 stainless steel. The bearing seat was a rectangular cuboid with dimensions of 54 × 40 × 75 mm^3 and featured a 42-mm-diameter hole for placing the bearing. The shaft did not directly contact the bearing seat. There were two 8.2-mm-diameter through-holes on the sides for securing it to the left and right frames, and three screw holes at the bottom for attaching it to the base plate. The base plate was a thin plate measuring 134 × 58 mm^2 with a thickness of 10 mm, used to secure the bearing seat and side plates. The side plates measured 134 × 100 × 18 mm^3 and were fixed to the base plate at the bottom and to the frame and bearing seat at the back. The front of the side plates had a 42-mm-diameter hole for placing the bearing. The bearing cover was a thin plate measuring 50 × 50 mm^2, designed to secure the bearing within the side plate and to prevent molten aluminum from splashing onto the bearing. The ladle's primary purpose was to scoop molten aluminum. It was designed to hold approximately 32 kg of molten aluminum and was made of ductile iron Si-Mo51. The analysis process using Ansys Workbench involved importing the model drawn in SolidWorks into Ansys, selecting materials and setting parameters, meshing the model, and setting boundary conditions. If the solution did not converge, the process involved checking material parameters and iterating until convergence was achieved and results were displayed.

In this study, two coupled modules were used: the steady-state thermal module and the static structural module. The main principle involved importing the temperature parameters from the thermal analysis into the static structural module. The structural module then considered the thermal expansion and changes in Young's modulus and yielded strength due to temperature increases. The boundary condition settings for both modules are explained below. For the thermal field, since the ladle was continuously working by being immersed in molten aluminum in an automated process, the inner wall of the ladle was set to a uniform temperature of 700 °C, as shown in Fig. 2(a). Considering heat dissipation, the entire working environment temperature was approximately 60 °C. Thus, all exposed surfaces of the mechanism were set with a



(a) (b)

Fig. 2. (Color online) Diagrams for (a) temperature and (b) convection setting surfaces of the investigated molten aluminum alloy casting mechanism.

convective heat transfer coefficient of 5 W/(m^2·°C) with the ambient air at 60 °C, as illustrated in Fig. 2(b). In the static field, the upper adapter plate was set as a fixed surface. The entire mechanism was subjected to downward gravitational acceleration. Given that the origin of the coordinate system was set at the center of the adapter seat, the point with coordinates $x = 170.5$, $y = -837.05$, $z = -254.1$ represented the free surface center of the ladle's maximum molten aluminum capacity. The acceleration was set to 9.8 m/s^2 and the liquid density to 2375 kg/m^3, corresponding to approximately 32 kg of molten aluminum.

3. Simulation Results and Discussion

In this study, we conducted a mesh convergence analysis using the equivalent stress (Von-Mises) in the static structural module for the overall model. The analysis was performed under the condition where hydrostatic pressure is applied to the ladle at high temperatures. The objective is to determine the maximum stress that the entire mechanism can withstand when thermal and mechanical equilibria are achieved. Owing to the large overall volume of the finite element model, the initial element count was set at 780060, with gradual increases in mesh density and the number of elements. As shown in Fig. 3, the equivalent stresses are 849.87 MPa with 780060 elements, 855.65 MPa with 937278 elements, 858.23 MPa with 972121 elements, 860.76 MPa with 982542 elements, 861.33 MPa with 996590 elements, 863.43 MPa with 1033150 elements, 863.2 MPa with 1091270 elements, and 864.31 MPa with 1286400 elements. Figure 3 shows that the stress begins to converge when the number of elements count reaches 1091270. To balance solution accuracy and computational efficiency, an element count of 1033150 was selected for the analysis.

In this study, the design software SolidWorks and the analysis software Ansys were utilized to simulate and analyze the aluminum alloy casting automation mechanism enduring high temperatures and pressures. The mechanism model was designed and drawn in SolidWorks, which also facilitated interference checks. After manufacturing the parts and assembling the machine, the material properties of each component were input into Ansys to construct an

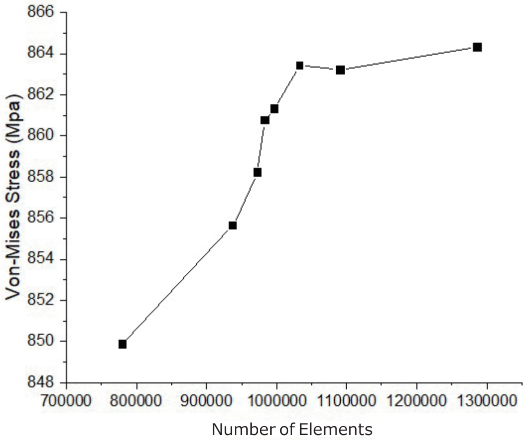


Fig. 3. Mesh convergence analysis of number of elements of the investigated molten aluminum alloy casting mechanism in finite element model.

analysis model for simulation. The aim was to determine whether the design of this mechanism meets the necessary requirements. The overall temperature field diagram is shown in Fig. 4, where purple indicates the highest temperature of 700 °C and gray represents the lowest temperature of 60 °C. Once thermal equilibrium is achieved, apart from the ambient temperature ensuring that the lowest temperature of the entire mechanism reaches 60 °C, only a small amount of heat is transferred through the ceramic bearings to the main structure. This design effectively prevents excessive heat from reaching the main body, which could reduce its strength.

It was anticipated that the shaft and bearings would experience significant stress, making it crucial to monitor their temperatures to ensure they do not become very high, which could lower mechanical properties and cause damage. Figure 5 provides detailed temperature distributions for the shaft and bearings. The analysis revealed that the chosen materials and design are effective in maintaining structural integrity under high-temperature conditions. The thermal insulation provided by the ceramic bearings successfully limits heat transfer to critical components. This finding underscores the importance of material selection and thermal management in the design of automated casting mechanisms. In this study, we confirmed that

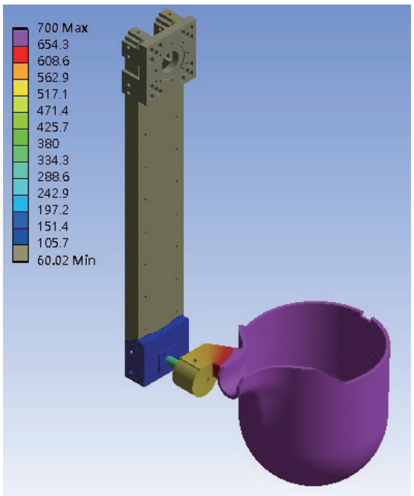


Fig. 4. (Color online) Overall temperature field (°C) of the investigated molten aluminum alloy casting mechanism.

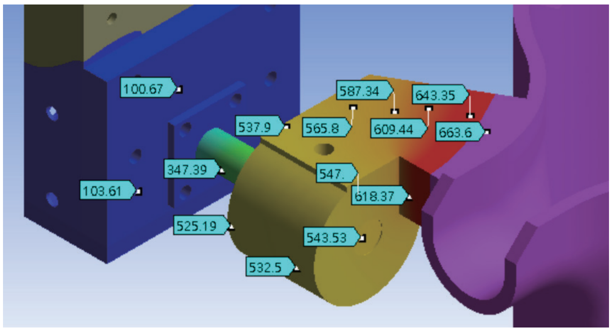


Fig. 5. (Color online) Local temperature field (°C) of the investigated molten aluminum alloy casting mechanism.

the current design meets operational requirements and provides a robust solution for automated aluminum alloy casting under high-temperature conditions.

In this study, the stress of the investigated molten aluminum alloy casting mechanism was generated not only by hydrostatic pressure but also by the pressure induced by thermal expansion. As shown in Fig. 6, areas with slightly higher stress are predominantly located in the shaft and bearing regions. Therefore, particular emphasis would be placed on this area. From Fig. 7, it is evident that the maximum equivalent stress of the investigated molten aluminum alloy casting mechanism occurs within the bearing, measuring 863.43 MPa. Moving on to examine the principal stress results, positive values denoted the tensile stress while negative values represented the compressive stress. From the simulation results, the maximum tensile stress of the investigated molten aluminum alloy casting mechanism experienced by the bearing was 579.72 MPa, while the maximum compressive stress was 787.36 MPa, both of which did not surpass the yield strength. Strain results in this study mirror stress patterns, occurring predominantly in the bearing. The displacement was mainly affected by not only mechanical

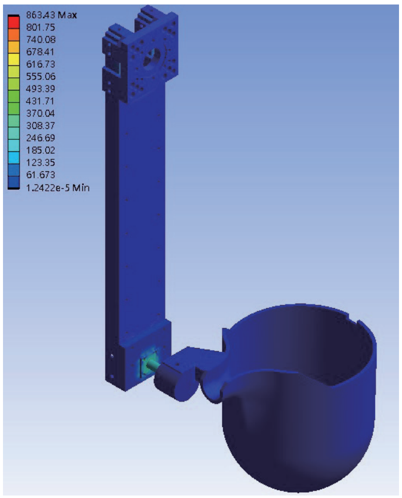


Fig. 6. (Color online) Overall equivalent stress field (MPa) of the investigated molten aluminum alloy casting mechanism.

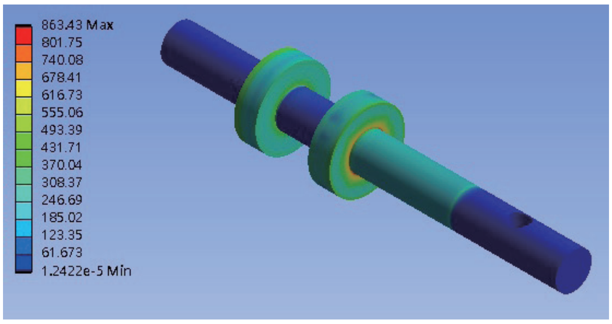


Fig. 7. (Color online) Equivalent stress field of the shaft and bearings (MPa) of the investigated molten aluminum alloy casting mechanism.

deformation but also thermal expansion-induced deformation. As shown in Fig. 8, the maximum displacement of the investigated molten aluminum alloy casting mechanism measured 9.1997 mm, occurring at the bottom of the ladle.

In this study, the shaft was a component that experiences relatively higher levels of stress and temperature. Therefore, in this section, we specifically compared the temperature and stress distributions of the shaft, as shown in Figs. 9 and 10, respectively. In comparison with relevant research data, even at a high temperature of 523 °C, the stress of the investigated molten aluminum alloy casting mechanism remained at 326.9 MPa. Thus, it can be concluded that the shaft has not reached its yield strength.

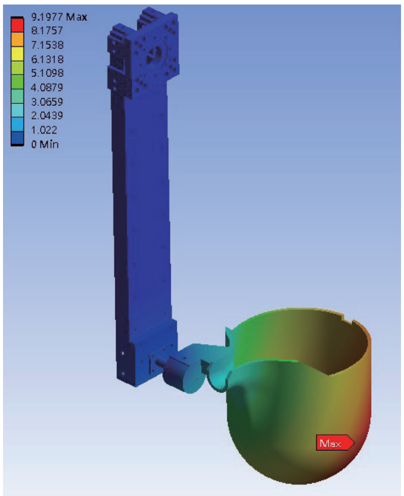


Fig. 8. (Color online) Diagram for the displacement results (mm) of the investigated molten aluminum alloy casting mechanism.

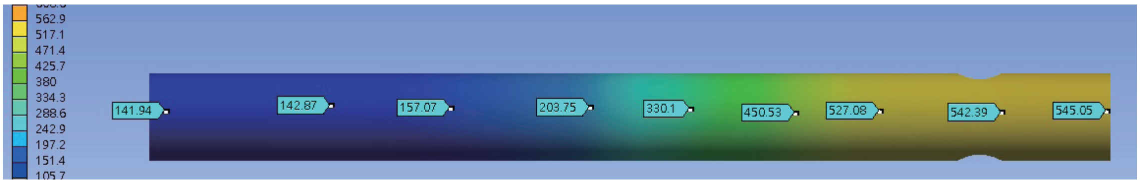


Fig. 9. (Color online) Diagram for the temperature distribution of the shaft of the investigated molten aluminum alloy casting mechanism.

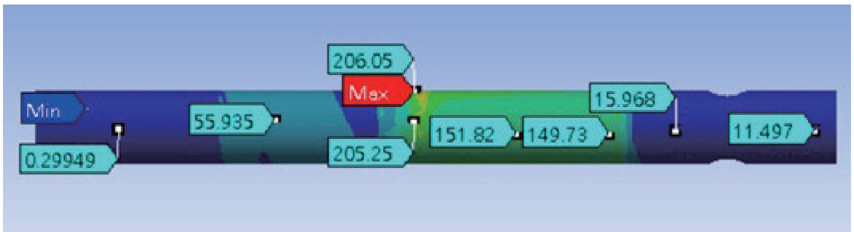


Fig. 10. (Color online) Diagram for the stress distribution of the shaft of the investigated molten aluminum alloy casting mechanism.

4. Conclusions

In this study, we focused on optimizing a molten aluminum alloy casting mechanism for enhanced durability and performance. Given the significant stress anticipated on the shaft and bearings within this mechanism, careful temperature monitoring is essential to prevent potential damage and maintain mechanical integrity. Through simulation, it was observed that stress levels stabilized with 1091270 elements. Therefore, for a balance between solution accuracy and computational efficiency, 1033150 elements were chosen for analysis. This design approach effectively shields the main body from excessive heat, preserving its structural integrity and strength. The analysis of the simulation results revealed that the maximum tensile stress experienced by the bearings was 579.72 MPa and the maximum compressive stress was 787.36 MPa, both well below the yield strength. Moreover, even at a high temperature of 523 ℃, the stress within the molten aluminum alloy casting mechanism remained at a manageable 326.9 MPa, as compared with relevant research findings. This underscores the robustness and reliability of the optimized design in maintaining performance under demanding conditions.

Acknowledgments

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