Development of a resistive system for the directional solidification of aluminum alloys under transient thermal conditions

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Abstract

Aluminum alloys are strategic materials for automotive and aerospace applications due to their low density, corrosion resistance, and favorable mechanical properties. Controlling solidification is essential for ensuring the final performance of cast components, and directional solidification is particularly relevant because it enables the imposition of controlled thermal gradients and the formation of columnar structures, allowing direct correlations between thermal parameters and microstructural evolution. In the resistive device developed in this study, the solidification of the Al–9%Ni alloy resulted in a predominantly columnar macrostructure, as confirmed by macrographic analysis along the ingot. Thermocouple measurements revealed thermal profiles characterized by progressively slower cooling as the distance from the metal/mold interface increased, indicating a decreasing cooling rate along the ingot. The liquidus isotherm position exhibited excellent mathematical fitting ($R^2 = 0.99$), accurately describing the evolution of the solidification front. The isotherm velocity also showed a decreasing trend with position, with a similarly high coefficient of determination ($R^2 = 0.99$). Likewise, the cooling rate decreased from approximately 7 °C/s at the base to below 3 °C/s in the upper regions. These findings demonstrate that the device produces an effectively unidirectional thermal gradient and allows reliable monitoring of solidification variables, highlighting its scientific and industrial potential.

Keywords: Directional solidification; Microstructural evolution; Thermal gradient control; Directional solidification device.

1 Introduction

According to De Souza and Rosa [1], the demand for new experiments, especially to deepen our understanding of the solidification process of metals and metallic alloys, is constantly increasing. This growth reflects the scientific and technological importance of this field, which plays a vital role in several areas of modern industry. The growing need of the industry for materials with superior properties, better quality, and increasingly specific applications drives this research Piorski et al. [2].

Aluminum is recognized as one of the most versatile engineering materials, thanks to an exceptional combination of properties. Its remarkable physical and chemical characteristics include low specific weight, corrosion resistance, high thermal and electrical conductivity, non-magnetic properties, and the ability to be infinitely. recycled Jesus et al. [3] Silva et al. [4].

The solidification of metallic alloys plays a fundamental role in the industry, as it allows the production of materials with specific mechanical and structural properties Gama et al. [5] Souza et al. [6]. The pursuit of more efficient and controlled solidification techniques has been a constant goal, aiming to improve the quality and properties of the produced materials Nascimento et al. [7] De Souza and Rosa [1]. In this context, the construction of unidirectional solidification devices under transient heat flow conditions has proven to be a promising approach. These devices allow more precise control of the solidification process, directly influencing the final properties of the material Rocha et al. [8] Santos et al. [9].

To create ingots with a completely columnar structure, unidirectional solidification devices must be used Cruz et al. [10]. This leads to the current project, which aims to develop a small device to guide the solidification process, enabling the investigation of the effects of solidification in aluminum alloys under transition scenarios with heat flow conditions Rocha et al. [8].

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2 Methodology

2.1 Device structure

The directional solidification device was developed and manufactured in the casting laboratory of the Federal Institute of Pará (IFPA), Belém campus. Figure 1 presents a flowchart detailing the main fabrication steps.

2.2 Construction of the device furnace and device structure

The fabrication of the device began with the manufacturing of the furnace in the casting laboratory, initiated by preparing the mold. Plywood was employed to define the geometry of the top, bottom, and lid. At the same time, refractory mortar and a refractory blanket were incorporated due to their high thermal resistance and low thermal conductivity. The blanket was used to line the entire interior and lid of the furnace, whereas the mortar acted as a structural filler. After a curing period of approximately five to seven days, the plywood mold was removed, yielding the furnace body. For the ingot mold, a steel tube with a diameter of 30 mm and a length of 150 mm was utilized.

To facilitate demolding, the tube was longitudinally sectioned, and clamps were applied to both ends to prevent leakage of molten metal and minimize ingot displacement during solidification. At the base of the system, a steel plate with a central hole was installed to accommodate the ingot mold, ensuring direct contact between the heat-extraction interface and the cooling medium (water), thereby accelerating heat transfer from the molten alloy. The dimensions of the metal–mold interface and the ingot mold are presented schematically in Figure 2 A. Figure 2B and 2C show the structure of the device with the following dimensions: the lid measures 265 mm in width, 265 mm in length, and 70 mm in height; the top part measures 265 mm by 265 mm in width and 160 mm in height; the bottom part has dimensions of 265 mm by 265 mm in width and 240 mm in height. It is worth noting that all these measurements already include the lining with the refractory blanket. The funnel has a height of 120 mm, and the central hole of the furnace has a diameter of 70 mm.

2.3 Resistive system of the device

To provide the heat required for directional solidification, the device employs an electric resistance fabricated from a nickel–chromium wire with a diameter of 0.90 mm, coiled into a spiral. The coil was placed inside a steel tube with a diameter of 50 mm and a length of 150 mm, which was subsequently inserted into a second tube with a diameter of 100 mm and the same length. This configuration resulted in a removable heating module that facilitates maintenance and replacement when necessary. The module can be inserted directly into the furnace chamber, with electric current supplied from the base and discharged through the top, thereby uniformly heating the chamber.

Temperature regulation was achieved using an AUTcontrol model AUT34T4 controller, which operates on dual voltage and within a range of –20 °C to 1250 °C.

A type K thermocouple was positioned inside the furnace to monitor the chamber temperature and to shut down the system automatically if the programmed working temperature was exceeded.

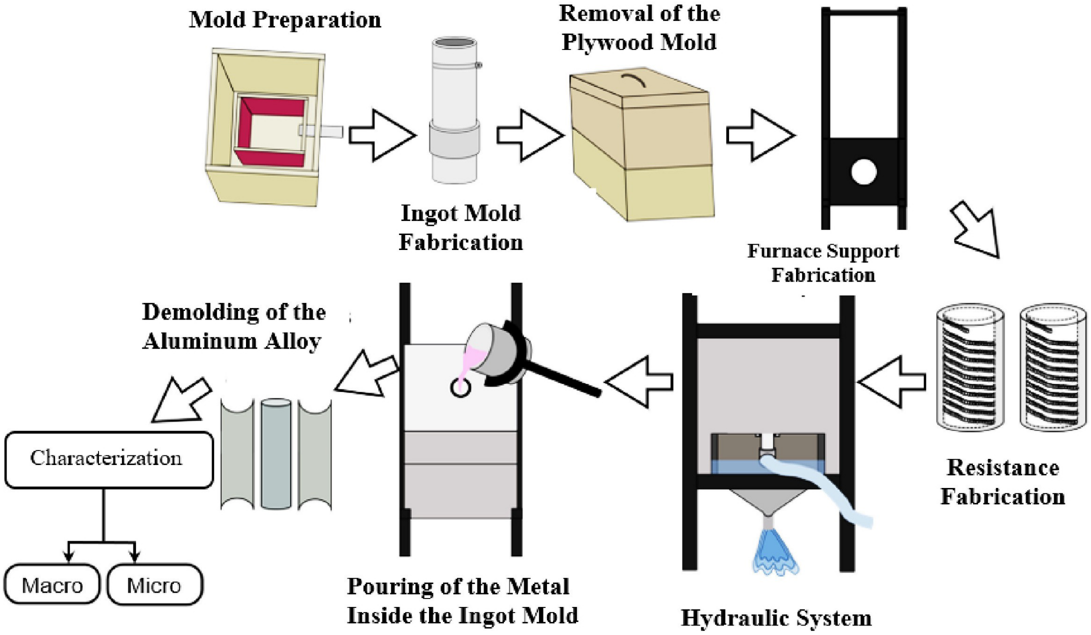

Figure 1. Flowchart of the fabrication of the unidirectional device.

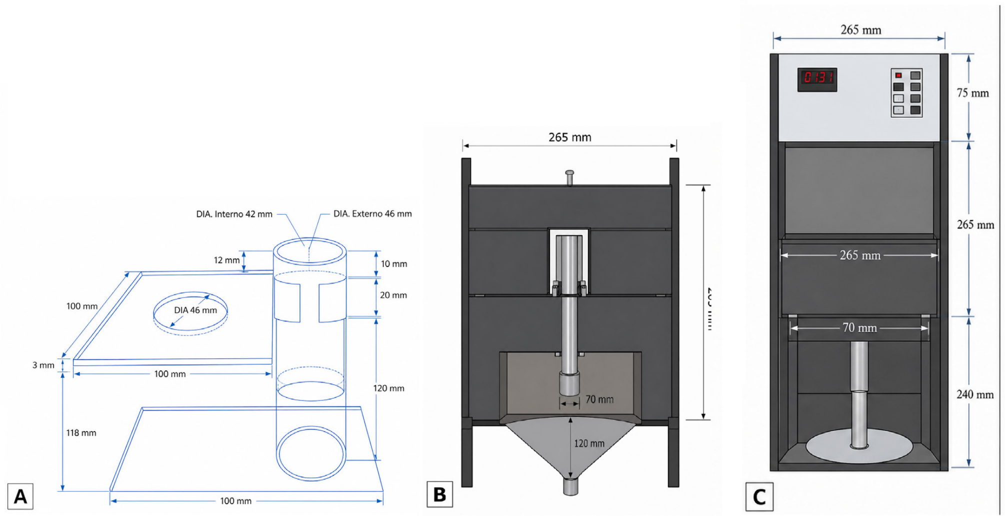

Figure 2. A, B and C. Dimensions of the metal/mold interface and the ingot mold and Basic structure of the device, side views and dimensions.

The controller also enabled the establishment of a desired operating temperature interval, ensuring stable heating conditions.

The electrical circuit incorporated a BTA41 triac transistor to regulate the current from the power grid to the resistor. For protection, two circuit breakers were installed—one for the thermocouple and another for the resistor—to safeguard against short circuits and overloads. In addition, five fuses were integrated into the system: two rated at 10 A and three rated at 0.3 A, interrupting the current flow when limits were exceeded. The operating temperature of the furnace was maintained at approximately 700 °C. Power was supplied through a 220 V AC industrial plug with a 32 A capacity, connected by four meters of copper wire with a cross-sectional area of 6 mm^2.

2.4 Hydraulic system

The hydraulic system was designed to ensure efficient extraction of heat from the ingot mold during solidification. It consisted of two steel tubes, each 150 mm in length and 16 mm in diameter, joined by a steel elbow. One tube was inserted into the ingot mold support (32 mm in diameter), establishing direct contact with the base of the ingot mold tray. The second tube was connected to a 4 m flexible hose, secured with clamps to guarantee sealing, with the opposite end attached to a faucet supplying the coolant.

The water jet impinged directly on the base of the cylindrical container, generating a force quantified by the product Kx, where K is the spring constant and x the measured deformation. Dividing this product by the cross-sectional area of the container yielded the pressure applied to the metal–mold interface. The system provided a pressure of $P = 2.09\ N/m^2$, corresponding to an average flow rate of 25 L/min. For drainage, a steel plate (100 × 100 mm) and a steel funnel (120 mm in length) were installed at the furnace base, directing the cooling liquid toward the drainage system. This configuration ensured a stable and continuous heat extraction during the solidification process.

2.5 Solidification of the Al–4%Ni Alloy for device testing

Prior to casting, a thin alumina layer was applied to the inner surface of the ingot mold to prevent contamination of the alloy by iron. The mold was then placed in the furnace for drying, minimizing potential interactions between the molten alloy and the mold material. Approximately 400 g of the Al–9%Ni alloy was melted in a graphite crucible inside an industrial furnace preheated to ~900 °C. Once fully liquid, the alloy was poured into the ingot mold, and the lid was immediately positioned to reduce heat losses to the environment.

During solidification, the cooling system was activated by opening the water faucet for approximately 20 minutes, ensuring complete extraction of heat from the ingot base. After upward vertical solidification, the ingot was longitudinally sectioned into two equal parts. One half was reserved for macrostructural analysis, while the other was subsequently prepared for microstructural characterization.

2.6 Macro and microstructural characterization

After longitudinal sectioning, half of the ingot was prepared for macrostructural analysis by surface grinding using abrasive papers ranging from grit 80 to 1200, with alternating grinding directions at each stage to minimize residual scratches. This procedure produced a polished surface suitable for macrostructural observation.

For microstructural examination, samples were mounted, ground, and polished using sequential abrasive papers of increasing fineness (100, 220, 320, 600, 1200, and 1500 grit), followed by final polishing with alumina suspension.

Chemical etching was performed using Poulton's reagent (5 ml HF, 30 ml HNO_3, 60 ml HCl, and 5 ml H_2O) to reveal the grain structure during macroanalysis. For microstructural analysis, a 0.5% HF aqueous solution was applied for 10–20 seconds to reveal dendritic features.

Micrographs were obtained with an optical microscope (Motic BA310 MET trinocular), equipped with an image processing system for documentation and quantitative analysis. This approach enabled the identification of grain morphology, dendritic structures, and solidification features, supporting correlations with the thermal conditions imposed during directional solidification.

3 Results and discussion

3.1 Device operation

Following the completion of the fabrication steps and experimental procedures, the device was successfully assembled and tested. Figure 3A shows the furnace in operation after preliminary evaluations, which included heating of the internal chamber and activation of the cooling system to simulate solidification conditions. The system demonstrated stable performance, confirming the effectiveness of the design for continuous operation. An automatic data acquisition system was integrated into the device, enabling real-time monitoring of temperature within the solidification chamber. This feature ensures accurate control of the thermal profile during experiments, a critical aspect for reproducibility and reliability of directional solidification studies. Figure 3B presents a schematic representation of the device, highlighting the arrangement of its main components and the configuration adopted to establish upward unidirectional solidification under transient heat flow conditions. The combination of resistive heating and water-cooled extraction provides a controlled environment suitable for investigating the thermal and microstructural evolution of aluminum alloys.

The internal chamber temperature was controlled by a thermocouple connected to the temperature controller, ensuring precise regulation of the heating cycle. This control strategy extended the service life of the resistive element by avoiding operation outside the desired range of 600–800 °C, which is suitable for the solidification of aluminum alloys.

Furthermore, maintaining the chamber within this range minimized degradation of the refractory lining, thereby enhancing the durability and reliability of the device under repeated experimental conditions.

3.2 Device parameters and heating curve of the solidification chamber

Table 1 summarizes the main parameters of the unidirectional solidification device, which define its general operating characteristics. The performance of the system is directly influenced by several variables, particularly the flow rate and pressure of the cooling water, since fluctuations in the hydraulic system can significantly affect the thermal conditions and, consequently, the structural behavior of the alloy during solidification. In addition, the geometric characteristics of the solidification chamber, such as its diameter and height, directly determine the final dimensions of the ingot. These parameters are essential for ensuring reproducibility in the experimental procedure and for enabling accurate correlation between thermal conditions and microstructural evolution.

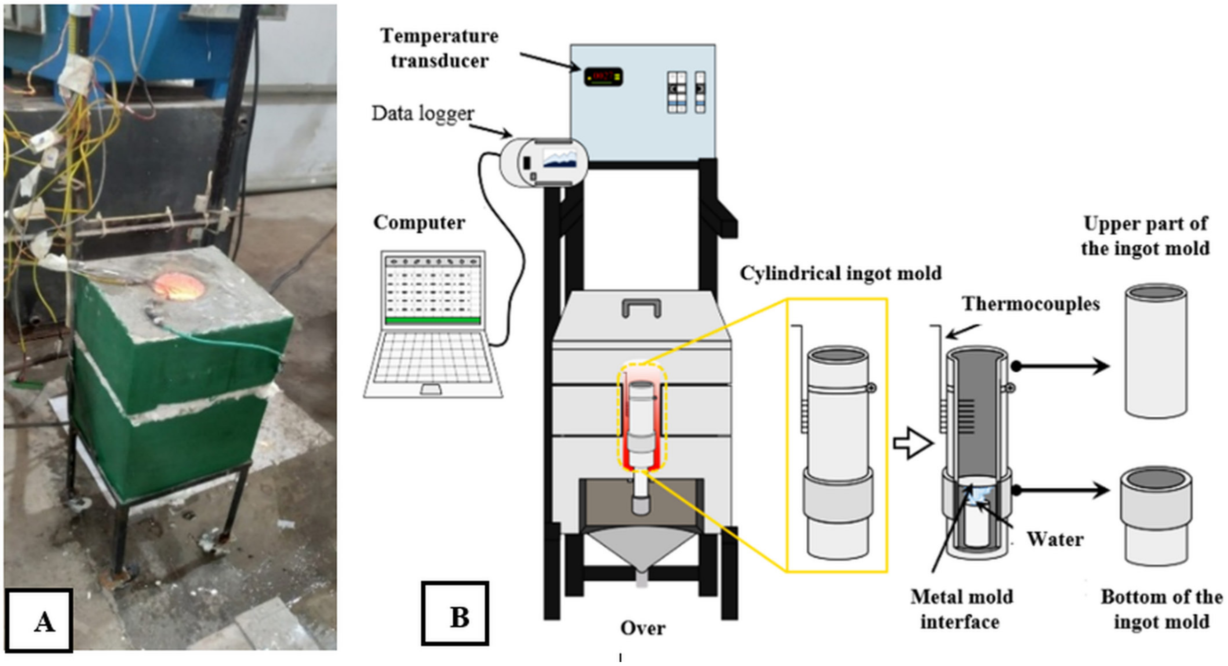

Figure 3. A) Furnace in operation; B) Schematic drawing of the unidirectional solidification device.

Table 1. Operating parameters of the unidirectional solidification device

Parameter	Value	Unit
Power	2.2	kW
Operating voltage	220	V
Chamber height	150	mm
Chamber diameter	50	mm
Chamber volume	117.75	cm^3
Water flow rate	25	L/min
Water pressure	2.09	N/m^2
Resistance wire diameter	0.90	mm
Resistance wire length	16	m
Resistance material	Ni–Cr steel	–

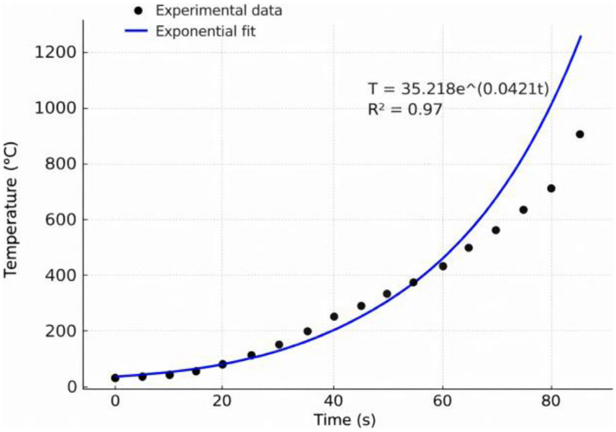

Figure 4. Temperature evolution during resistive heating of the solidification device.

The heating curve of the chamber, obtained through the internal thermocouple and temperature controller, revealed the efficiency of the device in rapidly reaching and maintaining the operational temperature required for aluminum alloy solidification.

The heating curve of the device, presented in Figure 4, demonstrates the efficiency of the resistive system in rapidly establishing the thermal conditions required for solidification experiments. The temperature evolution followed an exponential trend, with an excellent fit ($R^2 = 0.97$), reaching approximately 800 °C in nearly 80 s. This rapid response ensures that the device can operate within the desired range for aluminum alloy processing, minimizing heat losses and enhancing experimental reproducibility. The performance of the heating module confirms its suitability for controlled studies on directional solidification under transient conditions.

3.3 Thermal parameters and solidification process of the Al–9%Ni alloy

The thermal analysis performed with the developed device allowed the characterization of the unidirectional solidification behavior of the Al-9%Ni alloy. The cooling curves recorded by thermocouples at different positions along the ingot (Figure 5A) revealed a progressive decrease in the cooling rate with increasing distance from the metal/mold interface. This behavior confirms the establishment of a unidirectional thermal gradient, which is essential for the formation of columnar macrostructures.

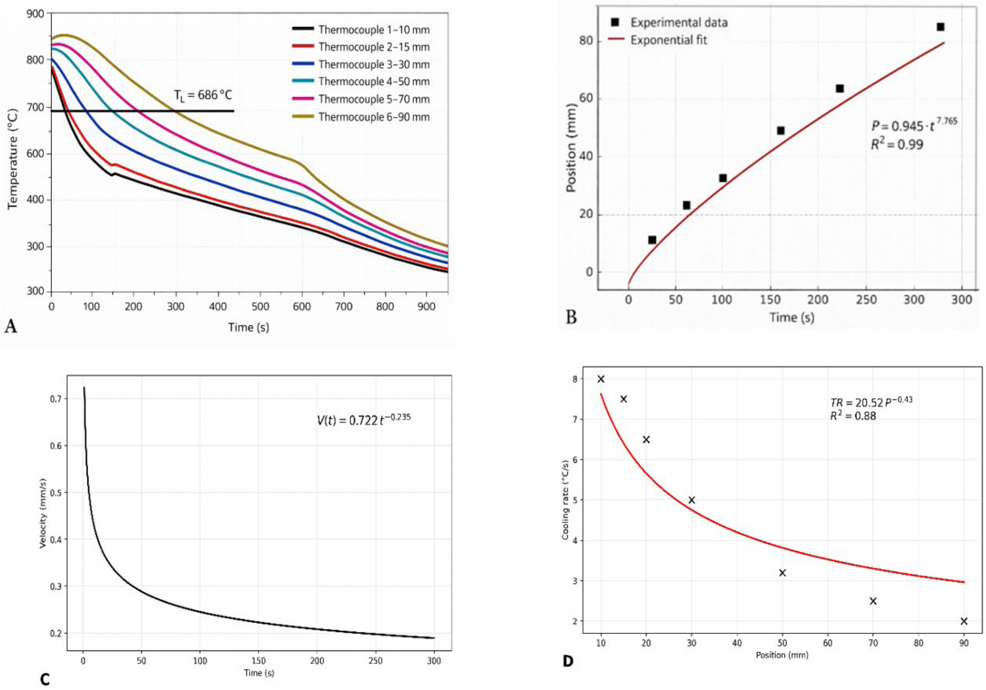

Figure 5. (A) Cooling curves recorded at different positions along the mold, showing the liquidus temperature (T_L ≈ 686 °C); (B) Experimental and fitted data of the position of the solid–liquid interface as a function of time; (C) Variation of the velocity of the liquidus isotherm (V) with position along the casting e portugues; (D) Thermal gradient (G) as a function of position.

The position of the liquidus isotherm as a function of time (Figure 5B) showed excellent agreement with the mathematical fit, with a high determination coefficient ($R^2 = 0.99$). This result demonstrates that the device enables reliable monitoring of the evolution of the solidification front, providing valuable data for quantitative analyses of the process kinetics. The velocity of the liquidus isotherm as a function of position (Figure 5C) exhibited a decreasing trend, indicating that the solidification front slows down as it moves away from the mold base.

This effect is directly associated with the reduction of the thermal gradient and the efficiency of heat extraction in the upper regions of the ingot. Finally, the cooling rate as a function of position (Figure 5D) confirmed the trends observed in the thermal curves, decreasing from approximately 7 °C/s at the base to about 2.5 °C/s in the upper regions. The good experimental fit ($R^2 = 0.88$) reinforces the reliability of the device for analyzing thermal solidification parameters under transient heat flow.

These results highlight that the developed system accurately reproduces unidirectional solidification conditions, enabling the study of thermal and structural parameters relevant to understanding dendritic growth in aluminum alloys and demonstrating that the device also exhibits strong versatility for application to different alloy systems, extending its usefulness beyond the Al–Ni system. Furthermore, this versatility suggests that future research may explore new alloy families and optimize process parameters such as thermal gradient, growth rate, and mold geometry, expanding the device's applicability to broader industrial contexts. These perspectives reinforce the scientific contribution of the present work and highlight the potential for continuity and expansion of the study, establishing the developed device as valuable tool for both academic and industrial solidification research.

The macrostructure of the Al–9%Ni alloy (Figure 6) exhibits columnar grains aligned with the heat flow direction, with a clear transition observed a few millimeters from the ingot base toward a stable columnar growth regime. This structural heterogeneity reflects the transient nature of the solidification process, in which thermal conditions gradually change along the ingot length.

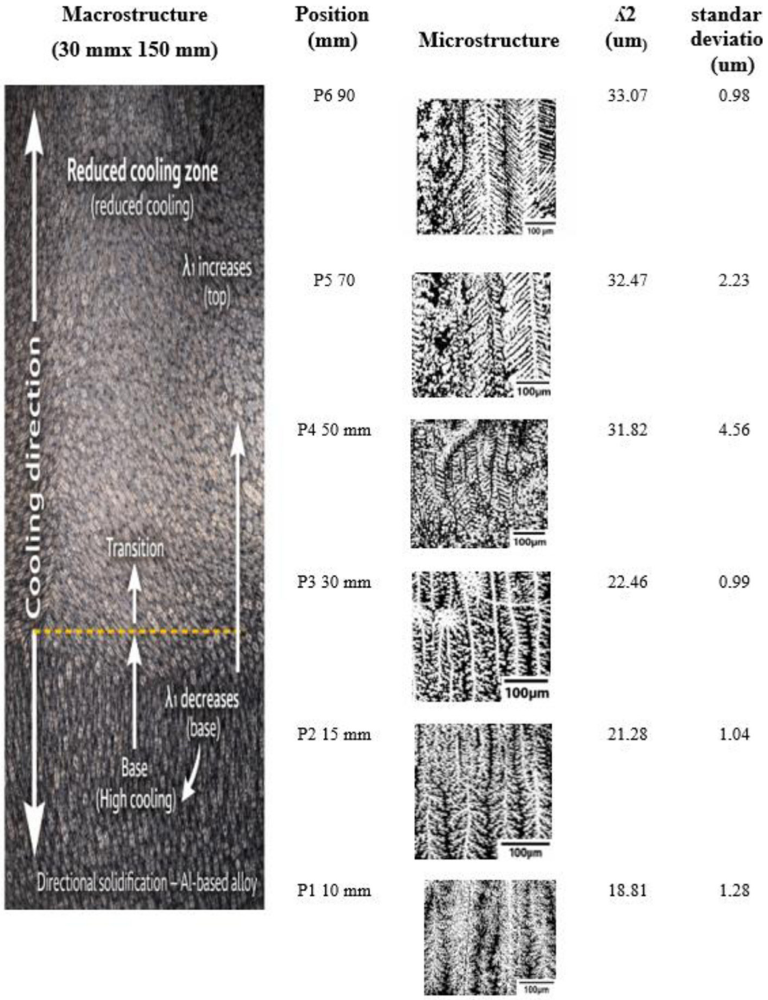

Figure 6. Longitudinal macrostructure of the Al–9%Ni alloy ingot, microstructures at different positions (P1–P6), and corresponding average secondary dendritic arm spacing (λ_2) with standard deviation. An increase in λ_2 toward the top is observed, associated with the reduction in cooling rate.

The microstructural images shown in Figure 6 reveal dendrites that become progressively more widely spaced from the base (P1) to the top (P6). This trend is confirmed by the measured secondary dendritic arm spacing (λ_2), which systematically increases along the ingot. The λ_2 measurements were performed according to the method proposed by McCartney and Hunt [11], ensuring accuracy and reliability in the characterization. Such behavior is directly associated with the cooling rate variation: at the base, where heat extraction is more intense, finer dendrites are formed; whereas in the upper regions, the reduced cooling rate favors coarser dendritic structures. These results demonstrate the capability of the device to reproduce the correlation between thermal parameters and structural evolution, validating its application in the study of solidification phenomena.

4 Conclusions

This study presented the development and validation of a unidirectional solidification device under transient heat flow conditions, applied to the Al–9%Ni alloy. The results demonstrated that the system, composed of refractory materials, electrical resistances, a temperature controller, and a hydraulic circuit, performed efficiently, ensuring proper control of the internal thermal environment and heat extraction at the ingot base.

Thermal analysis showed that the heating curve reached approximately 800 °C in about 80 seconds, confirming the fast response of the device. Cooling curves recorded by thermocouples indicated a progressive reduction in cooling rate along the ingot, with values around 7 °C/s at the base and below 3 °C/s at the top. This transient behavior was directly reflected in the resulting macro- and microstructures.

The macrostructure revealed an initial transition followed by the development of an extensive columnar zone aligned with the heat flow direction, confirming the efficiency of the device in establishing a unidirectional thermal gradient.

At the microstructural level, an increase in secondary dendritic arm spacing (λ_2) was observed from the base to the top, a behavior directly related to the decrease in cooling rate.

Overall, these results validate the developed device as a reliable and versatile tool for investigating thermal and structural parameters in aluminum alloys. In addition to the Al–Ni system studied here, the configuration of the device enables its application to other alloy families, broadening its industrial and scientific relevance. Future research may explore different alloy compositions, optimize the thermal gradient and growth rate, and evaluate the influence of mold geometry, further expanding the applicability and performance of the system.

References

1 De Souza V, Rosa DM. Characterization of the as-cast microstructure of the Al-40%Zn alloy with two Cu contents produced by unidirectional solidification under transient heat transfer. Revista Eletrônica de Materiais e Processos. 2019;14(2):78-90.

2 Piorski CMP Jr, Kakitani R, Cheung N, Bertelli F. Correlação entre parâmetros térmicos de solidificação, microestrutura e dureza para uma liga Al5% Cu0, 8% Mg antes e após o tratamento térmico T6. Tecnologica em Metalurgia, Materiais e Mineração. 2024;21:e3082. https://doi.org/10.4322/2176-1523.20243082.

3 Jesus W, Silva VL, Souza HRO, Costa TAPS, Rocha OFL, Nascimento LGS, et al. Thermal and Microstructural Characterization of the Multicomponent Alloy Al-33wt%Cu-1wt%Ni-1.2wt%Ta Solidified with Transient Heat Flow. Trends in Sciences. 2024;21(9):8029. https://doi.org/10.48048/tis.2024.8029.

4 Silva N, Silva MVM, Braga DS, Gomes LG, Nascimento LGS. Upward vertical unidirectional solidification of Al-Cu-Ni system alloys: a general review on the process, microstructure control, T6 heat treatment, and corrosion. Revista Delos. 2025;18(66):e4587. https://doi.org/10.55905/rdelosv18.n66-008.

5 Gama LGO, Leite YYFL, Lobo RB, Souza LA No, Silva MVM, Silva NCS, et al. Study of the influence of cooling rate on microstructure and corrosion resistance in Al-4%Cu-7.5%Ni and Al-4%Cu-13%Ni alloys unidirectionally solidified under transient heat flow. Revista Foco. 2025;18(1):e7413. https://doi.org/10.54751/revistafoco.v18n1-020.

6 Sousa N, Garção WJL, Chrisóstimo WB, Sales RC, Ferreira AF. Analysis of thermal variables and correlation with dendritic spacing and microsegregation in unidirectional solidification of the binary Al-4%Cu alloy. Cadernos UniFOA. 2019;14(40):5-17. https://doi.org/10.47385/cadunifoa.v14.n40.2991.

7 Nascimento L, Costa DS, Souza EG. Correlation between structures and hardness of Al-2.5%Ni, Al-4%Cu-2.5%Ni, Al-4%Ni, and Al-9%Ni alloys solidified under transient heat extraction. Revista Foco. 2024;17(5):e4949. https://doi.org/10.54751/revistafoco.v17n5-040.

8 Rocha O, Dias JM Fo, Costa TA, Vasconcelos AJ, Moreira AL, Kikushi R. Heat transfer coefficient at the metal/mold interface and thermal variables in horizontal directional solidification of Al-6%Cu alloy. HOLOS. 2013;5: 28-39. https://doi.org/10.15628/holos.2013.1483.

9 Santos LI, Cheung N, Lima TS. Influência nos parâmetros térmicos de solidificação, microestrutura e microdureza decorrente da adição de Sb na liga eutética Sn-Cu. Revista dos Trabalhos de Iniciação Científica da UNICAMP. 2018;(26). https://doi.org/10.20396/revpibic262018888.

10 Cruz K, Cheung N, Garcia A. Thermal parameters, macrostructure, and microstructure in directional solidification of the Al-20%Sn alloy. Tecnologica em Metalurgia, Materiais e Mineração. 2013;4(4):21-26. https://doi.org/10.4322/tmm.00404004.

11 McCartney DG, Hunt JD. Measurements of Cell and Dendrite Growth during Directional Solidification of Aluminium Alloys. Acta Metallurgica. 1981;29(11):1851-1863. https://doi.org/10.1016/0001-6160(81)90111-5.

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