Optimized Heating Strategies for Aluminum: A Theoretical and Experimental Study

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Abstract

In construction, heating aluminum components is occasionally necessary for tasks such as shaping, fitting, or performing repairs. Aluminum's high thermal conductivity and specific heat capacity make it difficult to achieve significant temperature increases using conventional methods [2]. One promising method involves dividing the boiling water into multiple portions, immersing the aluminum stick sequentially, and allowing thermal equilibrium to occur at each stage. This paper investigates an optimized heating strategy for aluminum, focusing on scenarios where traditional heating systems, such as blowtorches or induction heaters, are unavailable. The results will inform practical solutions for energy-efficient and effective aluminum heating in construction and related industries.

1 Introduction

Heating aluminum for construction tasks often relies on conventional systems like blowtorches. However, these methods are not always available or energy-efficient. Aluminum's high thermal conductivity and specific heat capacity exacerbate the challenge of achieving significant temperature increases [3]. A method involving sequential immersion in boiling water portions aims to mitigate these challenges by leveraging incremental temperature gains. This study develops a theoretical framework for this approach and performs experiments to validate the findings [4].

2 Methods

2.1 Theoretical Framework

The change in temperature of the aluminum rods was calculated using the principle of conservation of energy:

$$Q_{\text{absorbed}} = Q_{\text{released}}, \tag{1}$$

where

$$Q_{\text{absorbed}} = m_{\text{rod}} c_{\text{rod}} \Delta T_{\text{rod}},$$
$$Q_{\text{released}} = m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}}.$$

To account for heat loss to the air, Newton's Law of Cooling was applied:

$$Q_{\text{loss}} = hA(T_n - T_{\text{air}})\Delta t, \tag{2}$$

where h is the heat transfer coefficient, A is the surface area of the aluminum rod, T_n is the temperature of the rod, and T_{air} is the ambient air temperature.

The theoretical final temperature of the rod, when subjected to infinite cycles of heat equilibrium and considering heat loss, can be expressed as:

$$T_{\text{final}} = \frac{m_{\text{water}} c_{\text{water}} T_{\text{water}} + m_{\text{rod}} c_{\text{rod}} T_{\text{initial, rod}} - hA(T_{\text{average}} - T_{\text{air}})\Delta t}{m_{\text{water}} c_{\text{water}} + m_{\text{rod}} c_{\text{rod}}}, \tag{3}$$

where T_{average} is the average temperature of the rod during the process, approximated as the mean of $T_{\text{initial, rod}}$ and T_{final}.

The results for each rod are presented in Table 1.

Rod	Cycle	Final Temperature (°C)
1 (Brass)	1	70.04
1 (Brass)	2	81.28
1 (Brass)	3	86.39
1 (Brass)	4	89.31
1 (Brass)	5	91.20
1 (Brass)	6	92.46
2 (Steel)	1	68.54
2 (Steel)	2	79.63
2 (Steel)	3	84.87
2 (Steel)	4	87.94
2 (Steel)	5	89.92
2 (Steel)	6	91.21
3 (Steel)	1	54.98
3 (Steel)	2	67.87
3 (Steel)	3	74.52
3 (Steel)	4	78.59
3 (Steel)	5	81.25
3 (Steel)	6	83.06

Table 1: Theoretical final temperatures of rods after sequential heating.

2.2 Experimental Setup

Three rods were selected with the following parameters (detailed in Table 2). • QIXINSTAR Transparent High Precision Glass Thermometer 200 Celsius Degree Length 300mm Laboratory Chemistry Glassware

Rod	Material	Length (in.)	Width/Thickness (in.)
1	Brass	36	0.12
2	Steel	36	0.125
3	Steel	12	0.375

Table 2: Parameters of the rods used in the experiment.

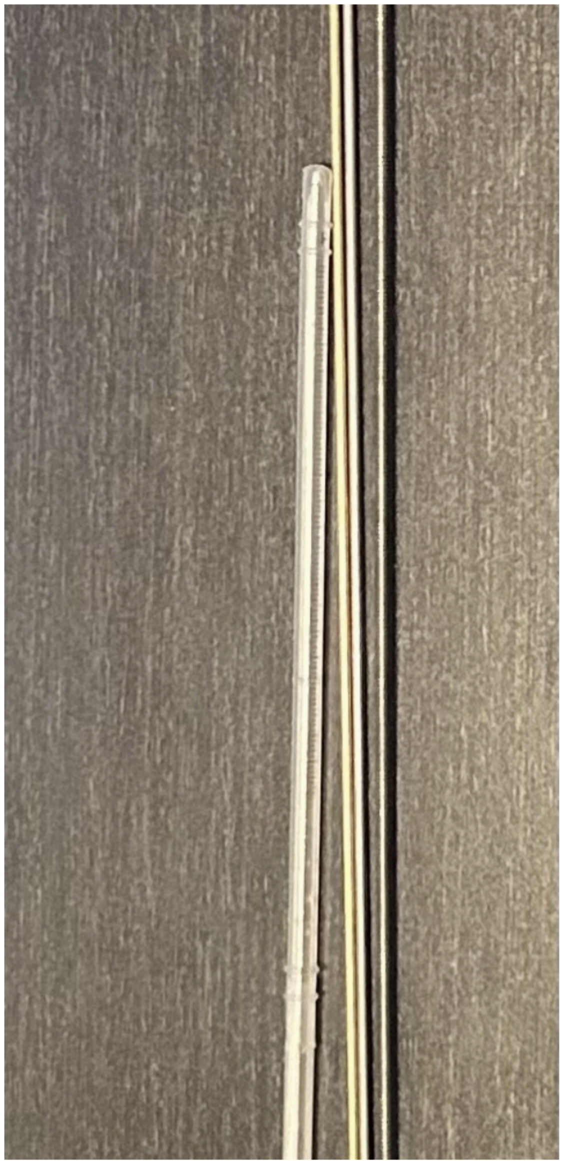

Figure 1: Experimental setup showing the brass rod, steel rod, threaded steel rod, and thermometer used in the experiment. From left to right: (1) Thermometer, (2) Brass rod, (3) Steel rod, (4) Threaded steel rod.

2.1.1 Procedure

100 mL of water was boiled using a kettle. 10 g of boiling water was measured and poured onto the metal rod. The rod and water were allowed to reach thermal equilibrium. The temperature of the rod was recorded using a thermometer. The process was repeated by

adding another 10 g of boiling water until all water is used up (6 cycles). These steps were performed for each rod (brass, steel, and threaded steel).

3 Results

The experimental results of heating the rods using sequential boiling water immersions are summarized in Table 3. The data includes the measured temperatures after each cycle for the brass rod, steel round rod, and fully threaded steel rod. Graphical representations of the temperature progression for each rod are provided in Figures 2, 3, and 4.

Cycle	Brass Rod (°C)	Steel Rod (°C)	Threaded Steel Rod (°C)
1	59.61	57.23	46.43
2	70.10	68.64	58.36
3	75.28	73.41	64.67
4	80.37	75.38	68.35
5	82.79	80.55	70.20
6	85.32	80.31	72.63

Table 3: Experimental results for temperature progression of rods across six cycles of heating.

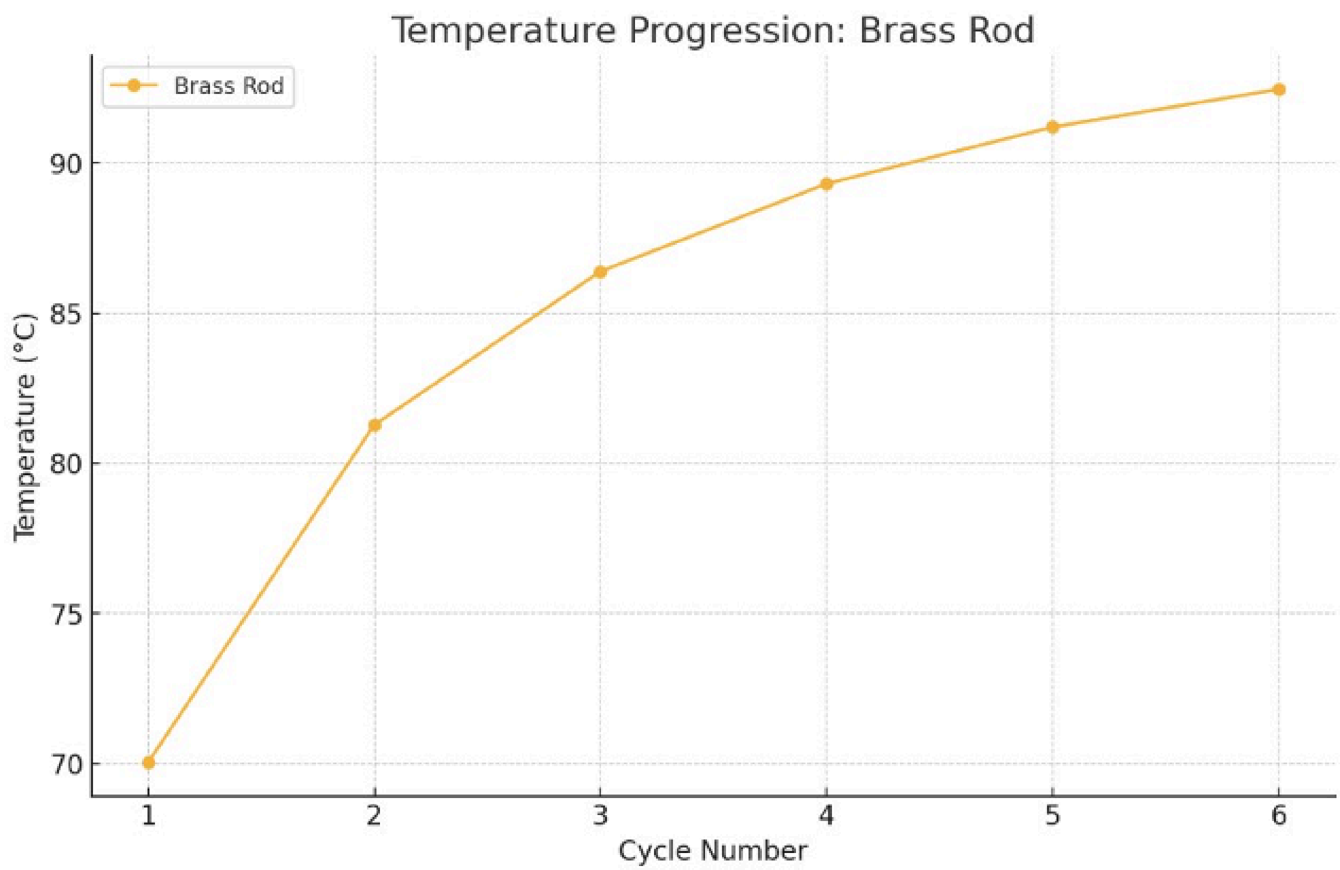

Figure 2: Temperature progression for the brass rod across six heating cycles.

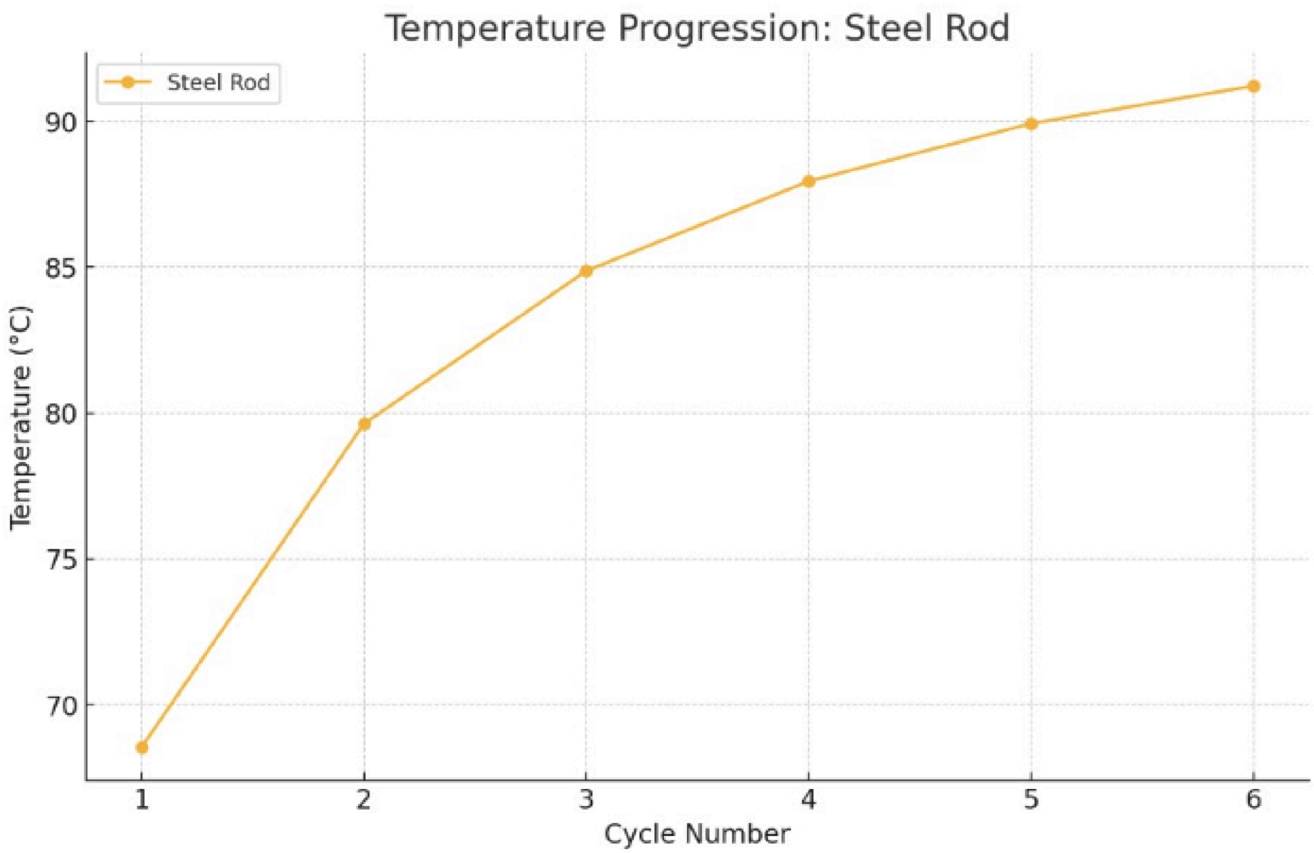

Figure 3: Temperature progression for the steel round rod across six heating cycles.

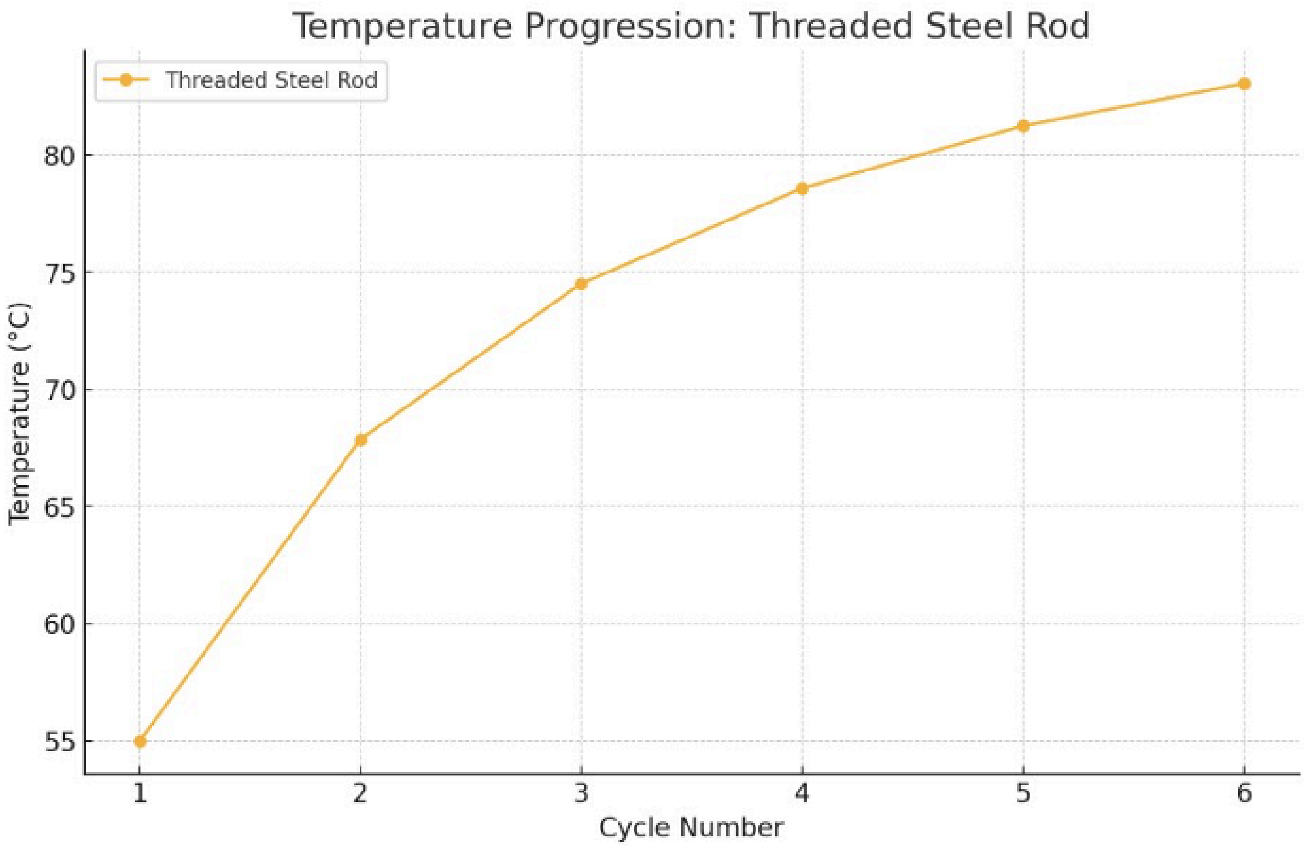

Figure 4: Temperature progression for the threaded steel rod across six heating cycles.

3.1 Observations and Analysis

- The brass rod achieved the highest final temperature of 85.32°C due to its relatively low heat capacity. - The steel round rod reached 80.31°C, slightly lower than the brass rod due to its higher heat capacity. - The threaded steel rod attained the lowest temperature of 72.63°C, primarily attributed to its larger surface area, which resulted in increased heat loss.

3.2 Percentage Error Analysis

Percentage errors were calculated as follows:

- Brass rod: 7.72%
- Steel rod: 11.95%
- Threaded steel rod: 12.56%

3.2.1 Brass Rod

The brass rod exhibited the lowest error among the three materials, with a percentage error of 7.72%. This is likely due to brass's lower specific heat capacity and relatively high thermal conductivity, which facilitate efficient heat absorption with minimal heat loss to the surroundings. Brass's properties also ensure uniform temperature distribution along the rod, reducing potential deviations. The observed error could be attributed to minor experimental inaccuracies, such as imperfect insulation or slight measurement errors in water volume or temperature.

3.2.2 Steel Rod

The steel rod showed a higher percentage error of 11.95%, which may be due to its higher specific heat capacity and lower thermal conductivity compared to brass. These properties require more precise control of heating cycles to achieve the predicted results. Heat losses due to convection and radiation were likely more significant, as steel retains heat for longer periods, allowing more time for dissipation to the surroundings. Measurement inaccuracies or ambient temperature fluctuations could have further amplified the deviation from theoretical predictions.

3.2.3 Threaded Steel Rod

The threaded steel rod exhibited the highest error of 12.56%, primarily due to its increased surface area, which results in greater heat loss to the environment. The threads introduce additional surface irregularities, exacerbating heat dissipation and slowing the temperature increase. The larger surface area-to-volume ratio means the rod loses heat more quickly than it absorbs, leading to a greater deviation from theoretical predictions. Uneven heat distribution caused by the structural design of the threads may have introduced localized cooling effects, further increasing the error.

3.2.4 General Observations and Recommendations

The percentage errors highlight the importance of considering heat loss mechanisms, such as convection, radiation, and ambient temperature variations, in theoretical models. To minimize discrepancies in future experiments:

- **Improve insulation:** Use materials with better-insulating properties to reduce heat loss during the heating process.

- **Enhance measurement precision:** Utilize more accurate instruments for temperature and volume measurements.
- **Optimize heating cycles:** Adjust the amount of boiling water and time intervals to account for material-specific properties and environmental factors.

This analysis demonstrates the robustness of the proposed heating strategy for aluminum, while also emphasizing areas where practical adjustments can further improve its accuracy and efficiency.

4 Applications

The study demonstrates a novel, energy-efficient approach to heating aluminum components, which can be applied in various domains. Sequential heating can be employed in remote or resource-constrained environments. It can provide a feasible alternative for shaping and bending aluminum without advanced tools. It can also serve as an excellent demonstration of heat transfer and energy conservation principles.

5 Discussion

The results obtained from the experiment align well with the theoretical predictions, with some deviations attributed to heat loss and material properties. The discussion is divided into key points to analyze the findings and provide context for the observed discrepancies.

5.1 Performance of Brass, Steel, and Threaded Steel Rods

5.1.1 Brass Rod

The brass rod showed the highest temperature increase among the three materials, reaching 92.46°C in six cycles. This result aligns with its relatively low specific heat capacity and high thermal conductivity, which allow for efficient heat absorption and uniform distribution. The percentage error for the brass rod was 7.72%, the lowest among the three materials. This indicates that the theoretical model accurately accounts for the thermal properties of brass and minimal heat loss.

5.1.2 Steel Rod

The steel rod achieved a final temperature of 91.21°C after six cycles. While its higher specific heat capacity compared to brass required more energy to raise its temperature, the error percentage was 11.95%. The discrepancy is likely due to steel's slower heat conduction and higher tendency to lose heat to the surroundings during the heating process.

5.1.3 Threaded Steel Rod

The threaded steel rod exhibited the lowest final temperature of 83.06°C. The larger surface area due to its threads increased heat loss through convection and radiation, resulting in a percentage error of 12.56%, the highest among the materials tested. The uneven surface of the threaded steel rod may also have caused localized cooling, contributing to greater deviations from theoretical predictions.

5.2 Sources of Error

Heat dissipation to the environment via convection, radiation, and conduction through the table surface likely contributed to the observed discrepancies. Minor inaccuracies in the measurement of water mass, temperature, and equilibrium time may have affected the results. The theoretical model assumes ideal conditions, such as perfect insulation and uniform heat transfer, which may not reflect real-world scenarios.

5.3 Implications and Practical Applications

The study demonstrates the feasibility of using small portions of boiling water for sequential heating as an alternative to traditional heating methods, particularly in resourcelimited environments. The results highlight the importance of considering materialspecific properties, such as specific heat capacity and thermal conductivity, when optimizing heating strategies. This technique could be employed in scenarios like construction, metalworking, and repair tasks where precise temperature control and energy efficiency are critical.

5.4 Recommendations for Future Work

Future experiments should incorporate better insulation to minimize heat loss and enhance the accuracy of the theoretical model. Using high-precision temperature sensors and automated systems for water application can reduce measurement uncertainties.. Testing additional materials with varying thermal properties can provide deeper insights into the effectiveness of the sequential heating method. Computational simulations can be used to model the heat transfer dynamics more accurately and predict the outcomes under varying conditions.

This discussion emphasizes the robustness of the proposed heating strategy while identifying areas for improvement and future research.

6 Bibliography

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