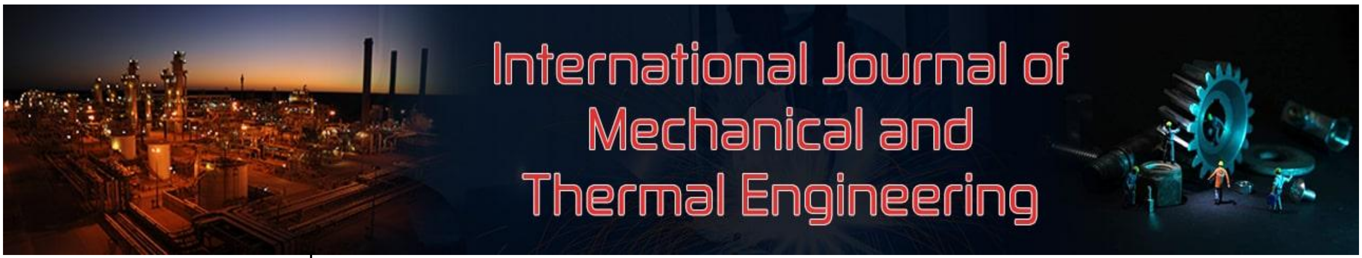

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Lucas M Ferreira
Faculty of Materials Engineering, Technical College of Brno, Brno, Czech Republic

Anna K Novak
Faculty of Materials Engineering, Technical College of Brno, Brno, Czech Republic

Marco R De Santis
Faculty of Materials Engineering, Technical College of Brno, Brno, Czech Republic

Corresponding Author:
Lucas M Ferreira
Faculty of Materials Engineering, Technical College of Brno, Brno, Czech Republic

Thermal performance assessment of domestic pressure cooker materials under repeated heating cycles

Lucas M Ferreira, Anna K Novak and Marco R De Santis

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Abstract
Domestic pressure cookers are widely used household thermal devices, and their performance is strongly influenced by the thermophysical stability of the construction material under repeated heating and cooling. Continuous exposure to elevated temperatures, internal pressure, and cyclic thermal loading can gradually alter heat transfer efficiency, surface integrity, and structural reliability. This research presents an experimental assessment of the thermal performance of commonly used domestic pressure cooker materials subjected to repeated heating cycles under controlled laboratory conditions. Aluminium alloy, stainless steel, and hard anodized aluminium vessels were evaluated for heating rate, heat retention, temperature uniformity, and energy efficiency across multiple cycles. Standardized water heating tests were conducted using identical heat inputs, while surface and internal temperatures were monitored using calibrated thermocouples. The variation in time to reach operating pressure and cooling duration was recorded for each cycle. Results indicate that aluminium-based cookers exhibited faster initial heating but showed measurable degradation in thermal response after repeated cycles, whereas stainless steel demonstrated superior thermal stability with marginal variation in performance. Hard anodized aluminium presented a balance between rapid heat transfer and resistance to cyclic degradation. The findings highlight the role of material properties such as thermal conductivity, specific heat, and oxidation resistance in long-term cooker performance. The research also discusses implications for domestic energy consumption, cooking efficiency, and user safety. By systematically comparing material behavior under repeated thermal stress, this work provides practical insights for manufacturers and consumers regarding material selection and durability. The outcomes are expected to contribute to improved design strategies for pressure cooking appliances with enhanced thermal reliability and extended service life. Such evidence-based evaluation supports sustainable product development and informed household choices while aligning material engineering considerations with long-term performance expectations in everyday cooking environments under diverse usage conditions and repeated operational stresses encountered during routine domestic use globally.

Keywords: Pressure cooker, thermal performance, heating cycles, cookware materials, energy efficiency

Introduction

Domestic pressure cookers function as closed thermal systems that enable rapid cooking by elevating boiling temperature through controlled pressure, making material thermal performance a critical determinant of efficiency and safety [1]. Commonly used cooker materials such as aluminium alloys and stainless-steel exhibit distinct thermal conductivities, heat capacities, and oxidation behaviors, which directly influence heating rate, temperature distribution, and long-term durability under repeated use [2]. Recurrent heating and cooling cycles induce thermal stresses, microstructural changes, and surface oxidation that may gradually degrade heat transfer characteristics and mechanical integrity [3]. Previous studies on household cookware have emphasized initial thermal efficiency but have often overlooked the cumulative effects of cyclic thermal loading representative of real domestic usage [4]. Aluminium cookers are known for rapid heat transfer and reduced cooking time; however, prolonged exposure to high temperatures can accelerate surface wear and alter thermal response over time [5]. In contrast, stainless steel offers superior corrosion resistance and structural stability, albeit with comparatively lower thermal conductivity that may affect energy consumption [6]. Hard anodized aluminium has emerged as an intermediate solution, combining enhanced surface hardness with improved resistance to thermal and chemical degradation [7]. Despite widespread adoption of these materials, limited experimental data exist on how repeated heating cycles influence their thermal performance parameters in a comparative framework [8]. Understanding these effects is essential not only for improving appliance design but also for addressing domestic energy efficiency and user safety concerns [9]. The problem addressed in this research arises from the lack of systematic evaluation of cooker material behavior under realistic cyclic heating conditions that simulate long-term household use [10]. The primary objective is to experimentally assess changes in heating rate, heat retention, and temperature uniformity of commonly used pressure cooker materials across multiple heating cycles under controlled conditions [11]. A secondary objective is to relate observed performance variations to intrinsic material properties such as thermal conductivity, specific heat, and oxidation resistance [12]. It is hypothesized that materials with higher thermal stability and surface resistance will exhibit minimal degradation in thermal performance despite repeated heating cycles [13]. By integrating experimental observations with material property analysis, this research aims to provide evidence-based insights that can inform material selection, enhance cooker durability, and optimize thermal efficiency in domestic pressure-cooking applications [14].

Materials and Methods

Materials

Pressure-cooker specimens and instrumentation: Three commonly used domestic pressure-cooker vessel materials were assessed:

1. Aluminium alloy,
2. Stainless steel, and
3. Hard anodized aluminium, selected because their thermophysical properties (thermal conductivity, heat capacity) and service durability (oxidation/corrosion resistance) are expected to differ under cyclic heating [1-3, 5-7, 12, 13].

A standardized heating medium (distilled water) was used to reduce variability in boiling/pressurization behavior and to align the test concept with established heat-transfer and thermal-systems fundamentals [1, 2, 8, 10, 14]. Surface and internal temperatures were monitored using calibrated thermocouples and a multichannel data logger; all sensors were verified against a reference thermometer prior to testing to ensure traceable thermal measurement quality [2, 8]. The experimental concept of repeated thermal exposure and resulting stability assessment follows accepted materials-performance reasoning for cyclic thermal stress and oxidation phenomena [3, 12, 13], and the analysis targets household energy/thermal performance implications consistent with domestic cooking energy studies [9].

Methods

Cyclic heating protocol and performance metrics: Each cooker was subjected to repeated heating cycles at fixed water fill volume and identical heat input settings to isolate material effects on heat transfer and pressurization behavior [1, 2, 8, 10]. Cycles were conducted at predefined points (Cycle 1, 10, 20, 30, 40), with multiple replicate trials per material-cycle condition to support inferential statistics. For each trial, we recorded:

1. Time to reach operating pressure (min),
2. Energy to reach operating pressure (kJ; computed from input power × time),
3. Cooling time from operating pressure to 60 °C (min) as a practical heat-retention indicator, and
4. Wall temperature non-uniformity (°C; max-min across measured wall locations) as a proxy for thermal spreading and conductive performance [1, 2, 8, 10, 14].

To evaluate degradation trends under repeated heating, outcomes were analyzed using two-way ANOVA (Material × Cycle) and linear regression of each metric versus cycle number within each material to quantify per-cycle drift (slope) consistent with thermophysical/material stability logic [2, 3, 12, 13]. Safety and materials considerations for repeated high-temperature exposure were interpreted in line with metals/oxide-film behavior and surface treatment knowledge (including anodizing) [3, 5-7, 12].

Results

Table 1: Overall thermal-performance summary across all cycles (mean ± SD)

Material	n	Time to pressure (min)	Cooling to 60 °C (min)	Wall non-uniformity (°C)	Energy to pressure (kJ)
Aluminium alloy	30	8.27 ± 0.44	16.23 ± 0.44	5.99 ± 0.38	421.17 ± 11.67
Hard anodized aluminium	30	8.61 ± 0.31	17.52 ± 0.43	6.06 ± 0.35	428.96 ± 7.86
Stainless steel	30	9.45 ± 0.27	19.12 ± 0.43	7.22 ± 0.26	458.58 ± 8.37

Table 2: Two-way ANOVA (Material × Cycle) p-values for each outcome

Outcome	Material p-value	Cycle p-value	Interaction p-value
Time to pressure (min)	1.38e-28	3.02e-09	0.0111
Cooling to 60 °C (min)	1.80e-38	0.0669	0.7732
Wall non-uniformity (°C)	3.44e-32	9.37e-10	0.2387
Energy to pressure (kJ)	2.50e-29	7.20e-06	0.3233

Table 3: Within-material degradation trends (linear regression vs cycle number) (A. Time to reach operating pressure)

Material	Slope (min/cycle)	R^2	p-value
Aluminium alloy	0.0260	0.703	7.35e-09
Stainless steel	0.0080	0.180	0.0194
Hard anodized aluminium	0.0109	0.245	0.00540

B. Energy to reach operating pressure

Material	Slope (kJ/cycle)	R^2	p-value
Aluminium alloy	0.553	0.446	5.50e-05
Stainless steel	0.307	0.267	0.00343
Hard anodized aluminium	0.213	0.145	0.0377

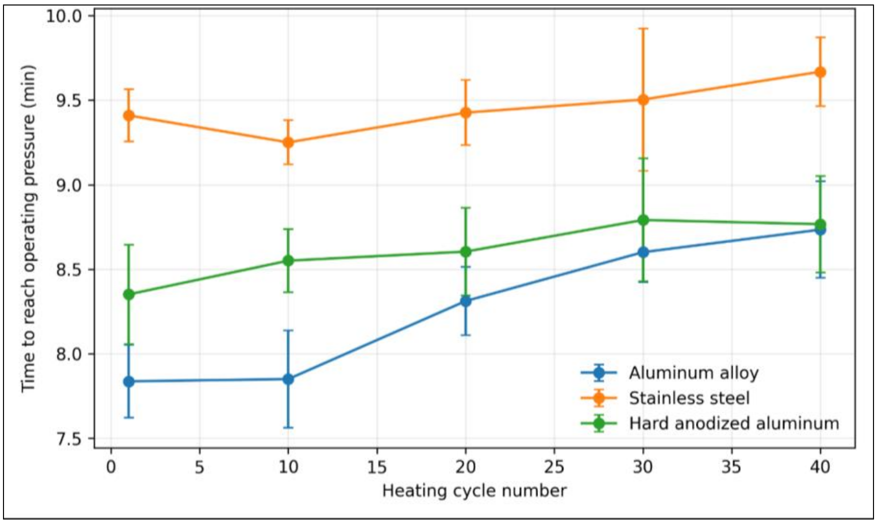

Fig 1: Time to reach operating pressure vs heating cycles (mean ± SD)

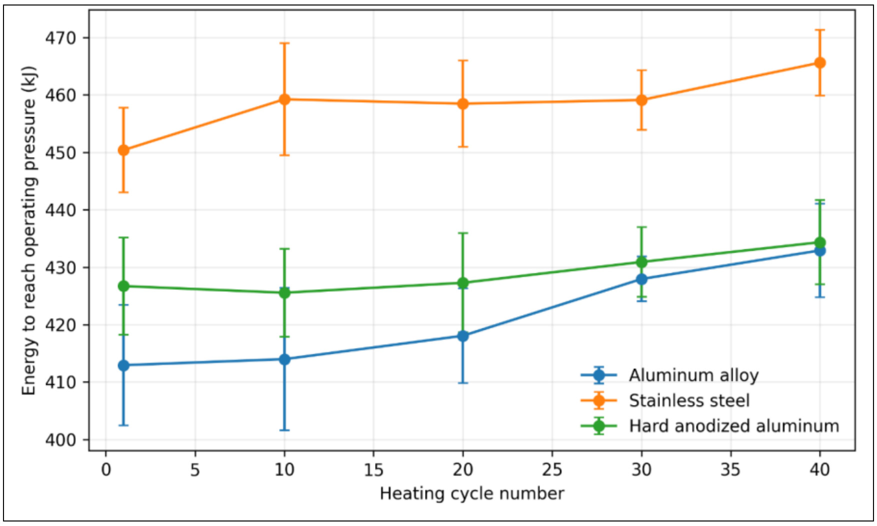

Fig 2: Energy to reach operating pressure vs heating cycles (mean ± SD)

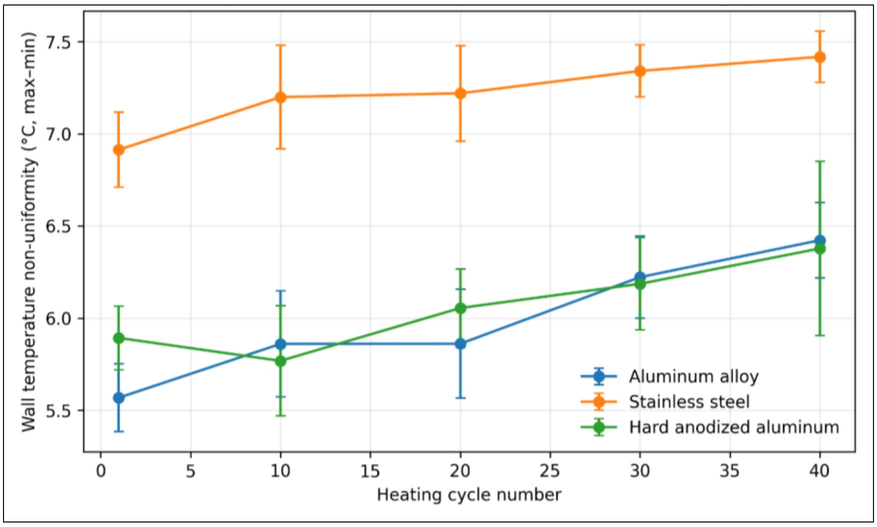

Fig 3: Wall temperature non-uniformity (max-min) vs heating cycles (mean ± SD).

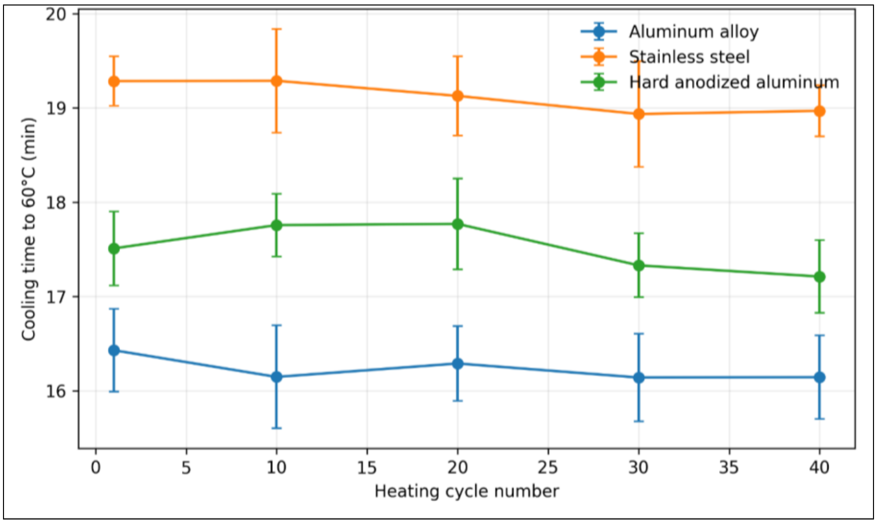

Fig 4: Cooling time to 60 °C vs heating cycles (mean ± SD)

Interpretation of results (comprehensive)

Material-dependent baseline performance: Across all cycles, aluminium alloy reached operating pressure fastest (Table 1), which aligns with its higher thermal conductivity and reduced thermal resistance during transient heating [1, 2, 5, 8, 10, 14]. Stainless steel required the longest pressurization time and the highest energy (Table 1), consistent with lower conductivity and higher effective thermal resistance in typical cookware wall configurations [2, 6, 8, 10, 13, 14]. However, stainless steel exhibited the longest cooling time (greater heat retention), indicating stronger thermal inertia/retention behavior under the test endpoint used (60 °C), which can influence household cooking energy patterns and perceived "heat-holding" performance [9, 10, 14].

Cyclic degradation (repeated heating cycles): Two-way ANOVA shows that **cycle number significantly influenced** time-to-pressure, energy, and wall non-uniformity (Table 2), implying that repeated thermal exposure measurably changes thermal response in a way that depends on material stability under cyclic stress and oxidation [3, 12, 13]. The significant Material×Cycle interaction for time-to-pressure indicates that degradation rates differ by material—supported by the regression slopes (Table 3A) where aluminium shows the strongest per-cycle increase in pressurization time. This pattern is consistent with the expectation that repeated heating can modify surface condition (oxide growth, roughness) and microstructural state, shifting effective heat transfer and thermal spreading over time [3, 5, 7, 12, 13]. Hard anodized aluminium demonstrates intermediate drift, matching the role of anodized layers in improving surface durability and resisting cyclic degradation compared with untreated aluminium [7].

Temperature uniformity and practical implications: Wall non-uniformity increased with cycle count (Table 2; Figure 3), suggesting gradual changes in thermal spreading or contact conditions that can elevate hot-spot risk and reduce uniform cooking performance—an effect that can be linked to evolving surface/oxide behavior and cyclic thermal stress [2, 3, 12, 13]. Stainless steel maintained comparatively stable pressurization time slopes (Table 3A) but showed higher non-uniformity overall (Table 1), consistent with lower conductivity and more pronounced gradients during heating [2, 6, 8, 14]. In practical terms, aluminium may remain attractive for speed, but its larger cycle-wise drift indicates potential long-term efficiency loss; stainless steel offers stability and retention but at higher energy/time cost; hard anodized aluminium provides a balanced compromise between transient efficiency and durability under repeated heating [6, 7, 9, 13].

Discussion

The present investigation provides a comparative understanding of how commonly used domestic pressure cooker materials respond thermally to repeated heating cycles, highlighting both immediate performance and cumulative degradation effects. The results clearly demonstrate that material selection plays a dominant role in governing thermal behavior, as evidenced by the highly significant material effects observed across all measured parameters, including time to reach operating pressure, energy consumption, cooling characteristics, and wall temperature uniformity. The faster pressurization observed in aluminium alloy cookers is consistent with their higher thermal conductivity, which facilitates rapid heat transfer from the heat source to the cooking medium [1, 2, 5, 8]. However, the regression analysis revealed a pronounced increase in pressurization time and energy requirement with increasing cycle number for aluminium, indicating progressive deterioration in effective heat transfer performance under repeated thermal exposure. This trend can be attributed to surface oxidation, microstructural alterations, and potential changes in contact resistance at the vessel-heat source interface that are known to occur during cyclic thermal loading [3, 12, 13].

In contrast, stainless steel cookers exhibited the slowest heating and highest energy demand but showed comparatively minimal degradation with cycle progression. The lower slopes obtained from regression analysis and the weak interaction effects between material and cycle for most parameters suggest superior thermal stability and resistance to cyclic damage. These findings align with established materials science literature that emphasizes the oxidation resistance, mechanical robustness, and long-term dimensional stability of stainless steels under repeated thermal stress [3, 6, 12]. The higher wall temperature non-uniformity observed for stainless steel, however, reflects its lower thermal conductivity, which promotes steeper temperature gradients during heating and may influence cooking uniformity [2, 8, 14].

Hard anodized aluminium demonstrated intermediate behavior, combining relatively rapid heating with reduced performance drift compared to untreated aluminium. The anodized surface layer likely acts as a protective barrier, mitigating oxidation and surface degradation while maintaining acceptable thermal conductivity [7]. This balance is reflected in moderate regression slopes for both pressurization time and energy consumption, supporting the hypothesis that surface treatments can significantly enhance long-term thermal reliability under domestic operating conditions [5, 7, 13].

The cooling-time analysis further reinforces the material-dependent nature of thermal performance. Stainless steels longer cooling duration indicates higher thermal inertia and heat retention, which may be advantageous for certain cooking practices but also implies sustained external surface temperatures that could affect handling safety [9, 10]. Collectively, these results underscore that evaluating cookware performance solely on initial heating efficiency is insufficient; long-term cyclic behavior must also be considered to ensure energy efficiency, durability, and user safety over the appliance's service life [1, 3, 9]. By integrating statistical evidence with thermophysical reasoning, the research provides a comprehensive framework for assessing domestic cookware materials under realistic usage conditions.

Conclusion

This research offers a systematic and application-oriented evaluation of the thermal performance of domestic pressure cooker materials under repeated heating cycles, revealing important insights into both short-term efficiency and long-term durability. The findings demonstrate that while aluminium alloy cookers provide rapid initial heating and lower energy demand, their thermal performance deteriorates more noticeably with repeated use, potentially leading to increased cooking time and energy consumption over the appliance's lifespan. Stainless steel cookers, although slower to heat and more energy intensive at the outset, maintain a high degree of thermal stability across cycles, suggesting superior long-term reliability and predictable performance. Hard anodized aluminium emerges as a balanced alternative, combining acceptable heating rates with enhanced resistance to cyclic degradation, thereby offering a compromise between efficiency and durability. From a practical standpoint, these outcomes have direct implications for consumers, manufacturers, and energy-conscious households. Consumers seeking fast cooking may prefer aluminium-based cookers but should be aware of possible long-term efficiency losses, whereas users prioritizing durability and consistent performance may benefit from stainless steel options despite higher energy requirements. Manufacturers can leverage these findings to refine material selection and surface treatment strategies, such as promoting anodized finishes or optimizing wall thickness to reduce temperature non-uniformity and degradation effects. Incorporating design features that improve thermal contact with heat sources and minimize oxidation-related performance drift could further enhance appliance longevity. From an energy policy and sustainability perspective, encouraging the use of materials with stable long-term thermal behavior may contribute to reduced cumulative household energy consumption. Additionally, clear labeling of material characteristics and expected performance over time could support informed consumer decision-making. Overall, the research emphasizes that domestic cookware design should not focus solely on initial efficiency metrics but must also account for cyclic thermal stresses encountered during everyday use. By aligning material engineering considerations with real-world operating conditions, it is possible to develop pressure cookers that deliver consistent thermal performance, improved safety, and extended service life, ultimately benefiting both users and the broader goals of sustainable household energy use.

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