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Thermal and Structural Analysis of a Cooking Pan Using COMSOL Multiphysics

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ABSTRACT

Cookware experiences strong temperature gradients during stovetop heating, causing thermal deformation and stress that influence performance, durability, and user safety. Although many studies examine heat transfer in cookware, most focus only on temperature distribution or heating efficiency. The combined thermal and structural behaviors of common cookware materials have not been studied using a fully coupled transient heat-transfer and structural-mechanics computational model. This work addresses that gap by examining how material properties influence temperature, thermally induced stress, and thermally induced deformation.

The main contribution of this study is the integration of a transient thermal model coupled with a structural model to evaluate how aluminum, carbon steel, and cast-iron pans respond to typical stovetop heating. The work provides a detailed comparison of how each material behaves when subjected to the same conditions and gives manufacturers new insight into the thermal-mechanical factors that influence warping, stress concentration, and long-term performance.

COMSOL Multiphysics 6.2 was used to simulate the heating process. A three-dimensional model was created in SolidWorks to represent the geometry of a standard pan. Conduction was modeled

as the primary heat-transfer mode. Convection and surface-to-ambient radiation boundary conditions were applied on exposed surfaces. The thermal model was coupled directly to a structural analysis to compute von Mises stress and deformation. Mesh refinement studies were performed to verify numerical stability, and hand calculations based on classic heat-flux relations and thermoelastic stress formulas were used to validate the accuracy of computational results.

Aluminum heated quickly and reached a uniform temperature profile early in the simulation, but it also showed a large amount of deformation. Carbon steel developed noticeable temperature gradients and produced the highest stress concentrations in the base and region where the base meets the sidewall. Cast iron warmed slowly due to its low thermal conductivity, but its high heat-retention properties caused both temperature and stress to continue increasing even after aluminum and carbon steel reached steady conditions.

The results show that material properties such as density, specific heat, thermal conductivity, coefficient of thermal expansion, Young's modulus, and Poisson's ratio play a major role in how cookware responds during typical heating conditions. These insights give manufacturers a practical way to evaluate materials before fabrication. By applying the same coupled thermal and structural simulation approach used in this study, manufacturers can compare candidate materials, identify options that are less prone to warping, and predict how different designs will perform under real heating scenarios. This method can be incorporated early in the product development process to guide material selection, assess multilayer constructions, and screen new or experimental material combinations with much lower cost and risk than physical prototyping.

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INTRODUCTION

Cookware performance depends heavily on how a material responds to heating during everyday use. When a pan is placed on a heat source, it experiences rapid heating, steep temperature gradients, and localized thermal expansion. Thermal expansion, thermal deformation, and thermal displacement will be used interchangeably throughout this report. These effects influence temperature uniformity, structural stability, and the overall durability of the cookware. Uneven heating can lead to hot spots that affect cooking behavior, while repeated thermal cycling contributes to long-term deformation such as warping.

Existing research in heat transfer and solid mechanics provides extensive information on thermal gradients, stress formation, and material behavior under high temperatures. However, very few studies focus specifically on cookware, and even fewer examine the effect of material properties such as thermal conductivity, specific heat, density, Young's modulus, and coefficient of thermal expansion on real cooking performance. Additionally, most prior work either simplifies geometry or studies thermal behavior without coupling it to mechanical deformation.

When a pan is exposed to direct heating, it undergoes a rapid increase in temperature and develops strong thermal gradients. Because the bottom surface is constrained by the heat source, thermal expansion becomes non-uniform. Significant stresses are generated throughout the pan. These effects depend heavily on material properties, resulting in different heating rates, temperature uniformity, and long-term deformation among materials such as aluminum, carbon steel, and cast iron. Although thermal and mechanical behavior of metals has been studied in general, very little research directly examines the combined thermal–mechanical response of cookware and how material selection affects performance.

This paper aims to bridge that gap by using COMSOL Multiphysics to simulate the coupled heat transfer and structural response of three common cookware materials. By modeling realistic heating conditions and capturing both temperature distribution and deformation, this study provides insight into hot-spot formation, stress development, structural reliability, and long-term durability. Understanding these behaviors is valuable for improving cookware design and extending product lifespan.

THEORY

1. Heat Transfer and Required Energy

When a material is heated, the temperature rise is determined by the amount of thermal energy absorbed. The energy needed to raise a material's temperature is given by:

$$Q = mc_p\Delta T \qquad (1)$$

where m is mass, c_p is specific heat, and ΔT is the temperature increase.
This relation provides the baseline for comparing how much heat each material requires to reach the same final temperature.

2. Pan Geometry, Volume, and Mass

The pan base is modeled as a flat plate with known area and uniform thickness. Its volume is computed using:

$$V = At \qquad (2)$$

The mass of each material is then found from:

$$m = \rho V \qquad (3)$$

Mass strongly affects heating behavior: heavier pans absorb more energy before increasing in temperature.

3. Applied Heat Flux

The burner transfers heat into the pan through the bottom surface. The applied heat flux is:

$$q'' = \frac{P}{A} \qquad (4)$$

where P is burner power and A is the heated area.

Real stoves deliver less than their rated power due to conduction, convection, and radiation losses. This is accounted for by multiplying the ideal heat flux by stove efficiency:

$$q''_{\text{eff}} = \eta q'' \qquad (5).$$

This provides a realistic measure of heat.

4. Heating Time

The time required for a pan to reach a target temperature is determined by dividing the energy required by the effective stove power:

$$t = \frac{Q}{\eta P} \qquad (6)$$

This equation links material properties to heating rate and allows comparison between gas, electric, and induction systems.

5. Thermal Expansion

When heated, materials expand according to:

$$\Delta L = \alpha L_0 \Delta T \qquad (7)$$

where α is the coefficient of thermal expansion. L_0 is the original length of the pan, and $\Delta T$is the change in temperature.

6. Thermally Induced Stress

If thermal expansion is constrained or occurs unevenly, internal stresses develop. Thermoelastic stress is estimated using:

$$\sigma = E\alpha\Delta T \qquad (8)$$

where $E$is Young's modulus.
Materials with high stiffness or large thermal gradients can develop large thermal stresses, increasing the likelihood of deformation.

7. Numerical Modeling in COMSOL

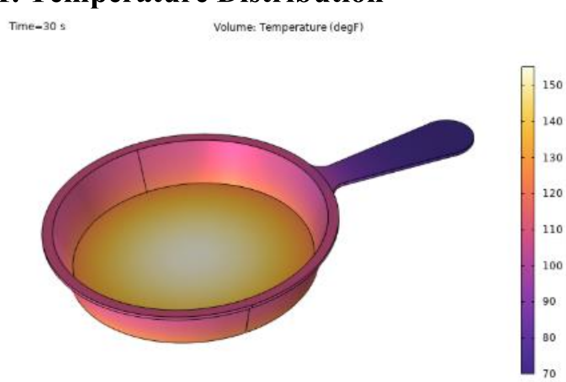
Heat Transfer in Solids and Solid Mechanics modules were coupled to simulate temperature, deformation, and von Mises stress under transient heating. The SolidWorks geometry, boundary conditions, and mesh settings used in the simulation are described in the procedure section, and plots appear in the COMSOL simulation results section.

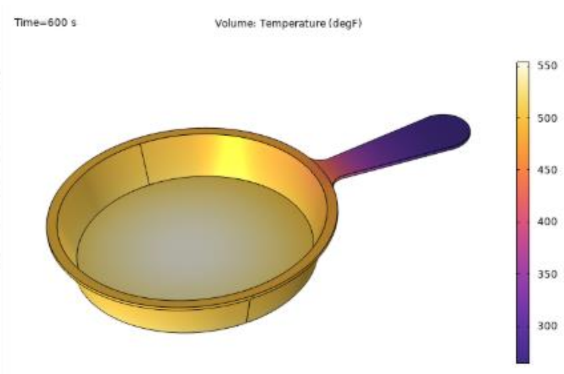
PROCEDURE

The cooking pan geometry was first created in SolidWorks. The file was saved as a .SLDPRT and imported into COMSOL using the CAD Import Module. Each material (aluminum, cast iron, and carbon steel) was assigned to the geometry using the properties listed in Table A1. The Heat Transfer in Solids physics interface was added to model transient heating, and the Solid Mechanics interface was added to compute thermal expansion and stress. Multiphysics thermal expansion coupling was enabled to link temperature changes to deformation. The initial temperature of the entire pan was set to 68 °F. A uniform heat flux of 26,315 W/m² was applied to the bottom surface to represent burner heating. All other external surfaces were exposed to surface-to-ambient radiation with an emissivity of each material was calculated using the material's efficiency. The natural convection of the pan was set to h=15 W/m²·K. The bottom central region of the pan was set as a fixed boundary to represent contact with a stovetop, while all other surfaces were set to be free. A physics-controlled mesh using the Normal setting was generated. Automatic refinement occurred along curved edges and the handle where higher stress gradients were expected. A time-dependent study was configured from 0 to 600 seconds with steps of 30 seconds. The simulation was run separately for aluminum, cast iron, and carbon steel. For each material, the temperature distribution, von Mises stress, and thermal displacement were recorded at 30 seconds and 600 seconds which is 10 minutes. Maximum values of temperature, deformation, and stress were extracted from the COMSOL results. Plots of temperature distribution, thermal deformation, and thermal stress were generated for each material. Analytical calculations were performed to compare heating time differences, thermal gradients, stress development, and deformation behavior with the simulation results. These calculations included temperature rise, pan volume, material mass, required heating energy, heat flux, effective heat flux, heating time for each stove type, thermal expansion, and thermal stress. All analytical calculations are documented in the appendix.

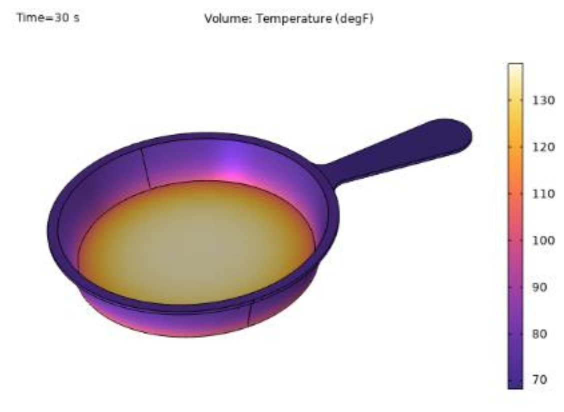
COMSOL SIMULATION RESULTS

1. Temperature Distribution





Figures 1. Temperature distribution for aluminum pan at 30 seconds
Figures 2. Temperature distribution for aluminum pan at 600 seconds
(Uniform, Rapid heat distribution, Lower maximum temperature)



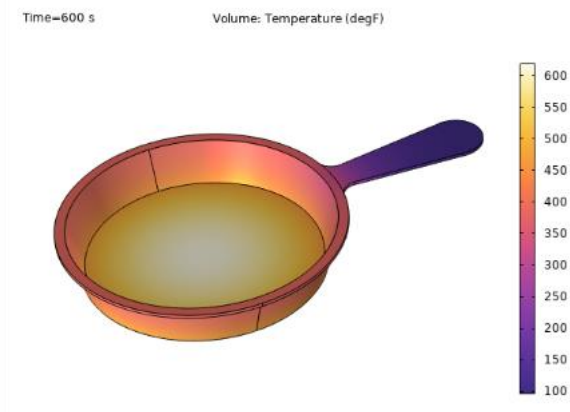
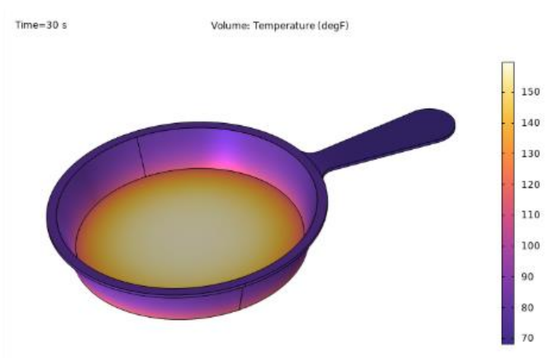


Figure 3. Temperature distribution for steel pan at 30 seconds
Figure 4. Temperature distribution for steel pan 600 seconds
(Non-uniform heat distribution, Slower heat distribution than Aluminum, Higher max temperature than aluminum)



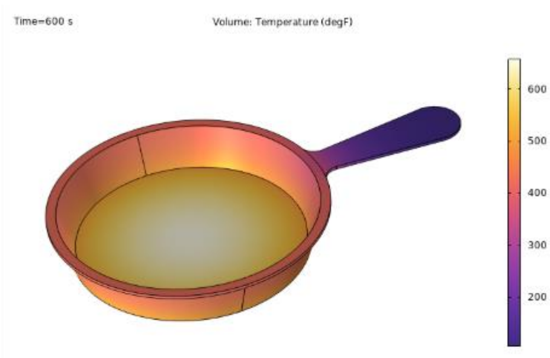
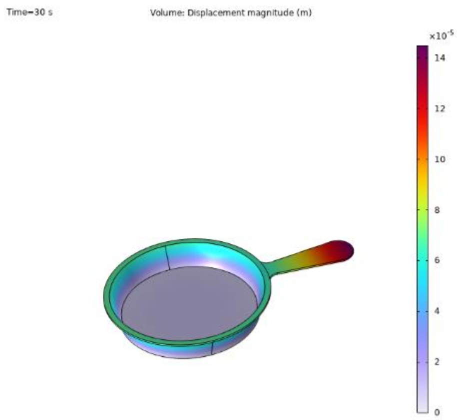


Figure 5. Temperature distribution for cast iron pan at 30 seconds
Figure 6. Temperature distribution for cast iron pan at 600 seconds
(Similar to steel, Higher minimum temperature at 600 seconds than steel)

2. Thermal Deformation



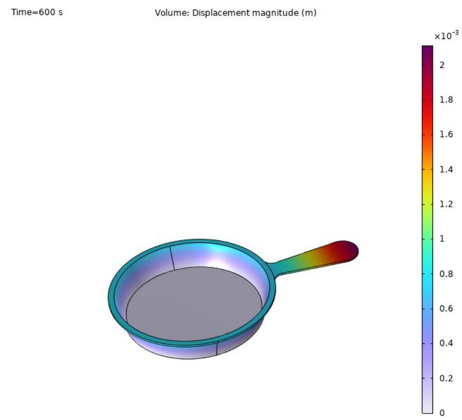
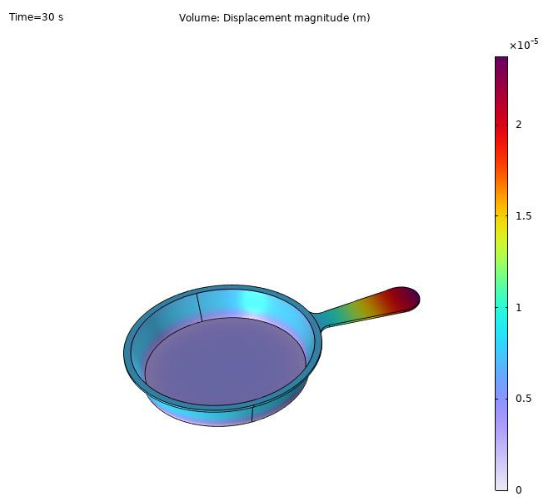


Figure 7: Thermal deformation of aluminum pan at 30 seconds
Figure 8: Thermal deformation of aluminum pan at 30 seconds
(Thermal deformation increases as distance from heat source increases.)



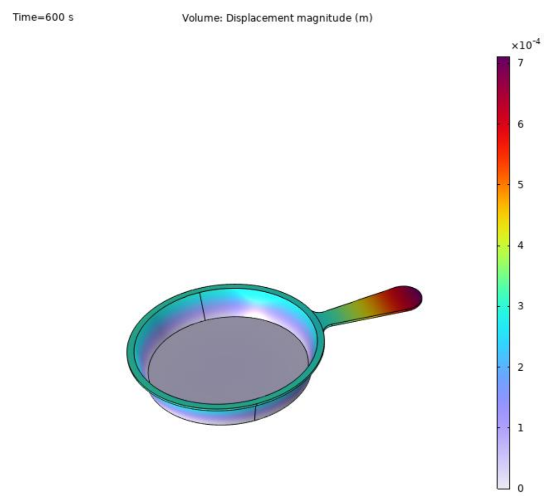
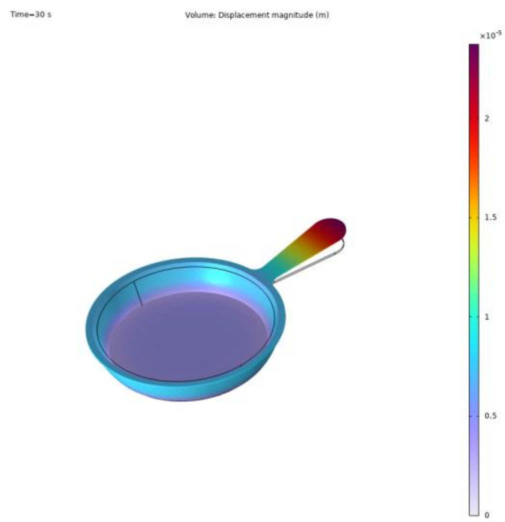


Figure 7: Thermal deformation of carbon steel pan at 30 seconds
Figure 8: Thermal deformation of carbon steel pan at 600 seconds
(Thermal deformation at 30 seconds is high in the center due to the heat source, Dissipates throughout the pan over time)



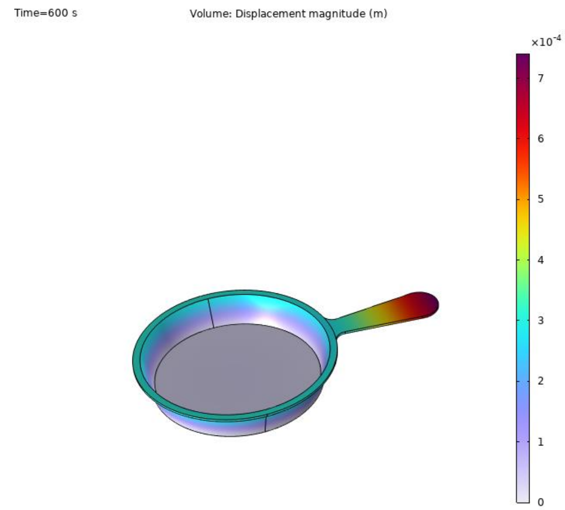
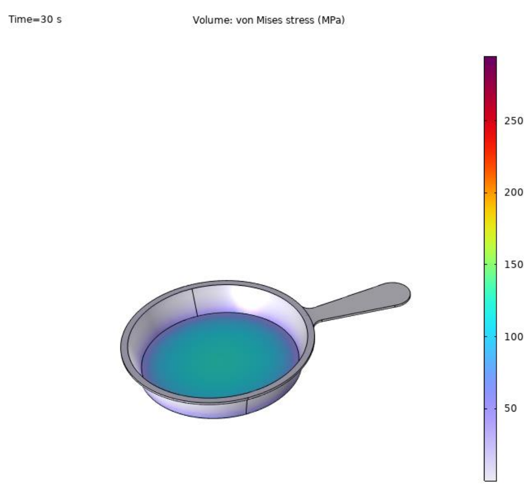


Figure 9: Thermal deformation of cast iron pan at 30 seconds
Figure 10: Thermal deformation of cast iron pan at 600 seconds
(Thermal deformation at 30 seconds is high in the center due to the heat source, Dissipates throughout the pan over time)

3. Thermal Stress Distribution
Note : Stress values shown represent upper-bound elastic stresses due to the linear elastic material model and constrained thermal expansion.



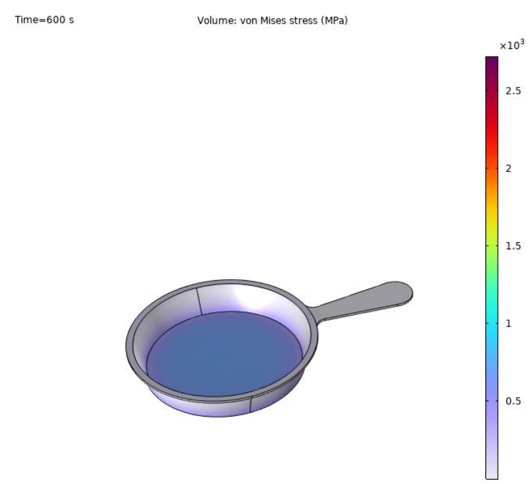
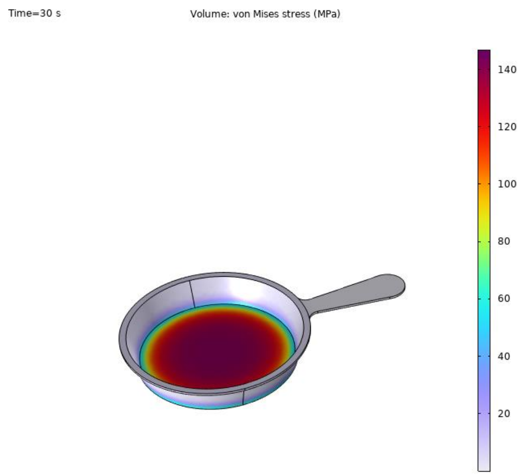


Figure 11: Von Mises thermal stress for the aluminum pan at 30 seconds
Figure 12. Von Mises thermal stress for the aluminum pan at 600 seconds
(High thermal stress at base of pan, Stress spreads over time)



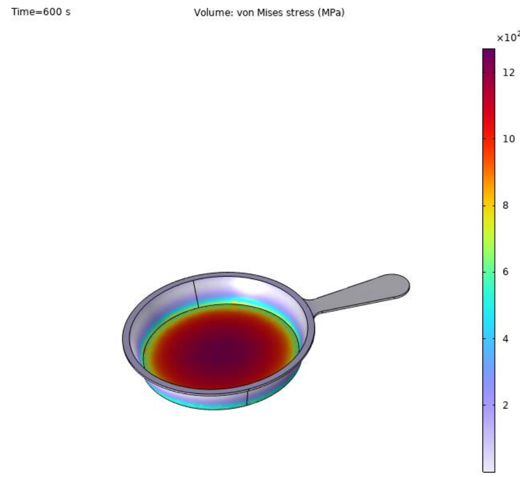
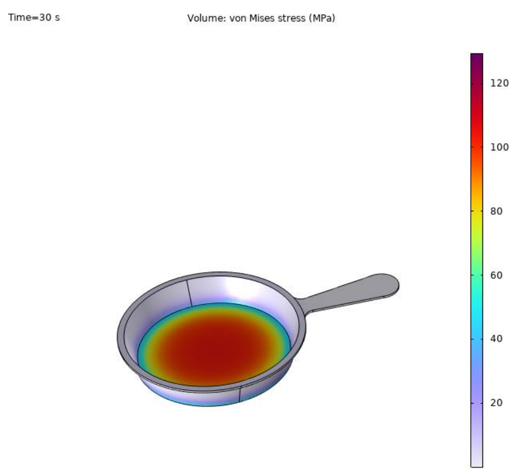


Figure 13. Von Mises thermal stress for the carbon-steel pan at 30 s.
Figure 14: Von Mises thermal stress for the carbon-steel pan at 600 s.
(Higher intensity of stress is experienced compared to aluminum, Thermal stress intensified and expands with time)



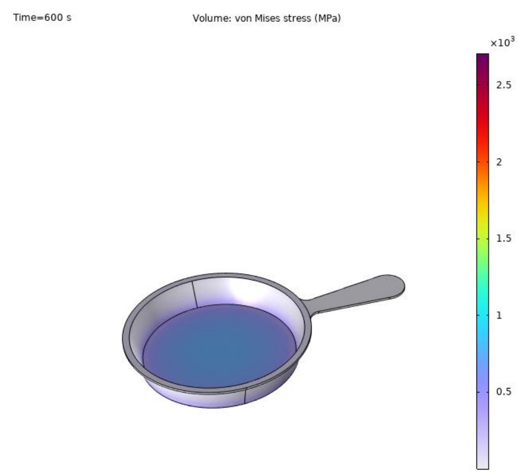
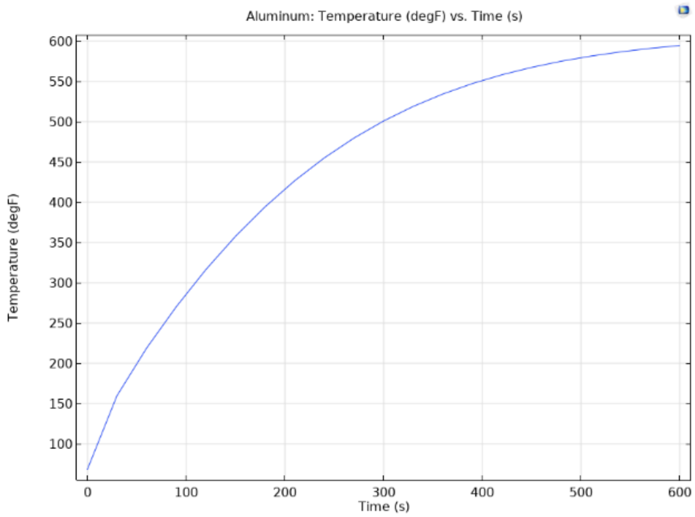
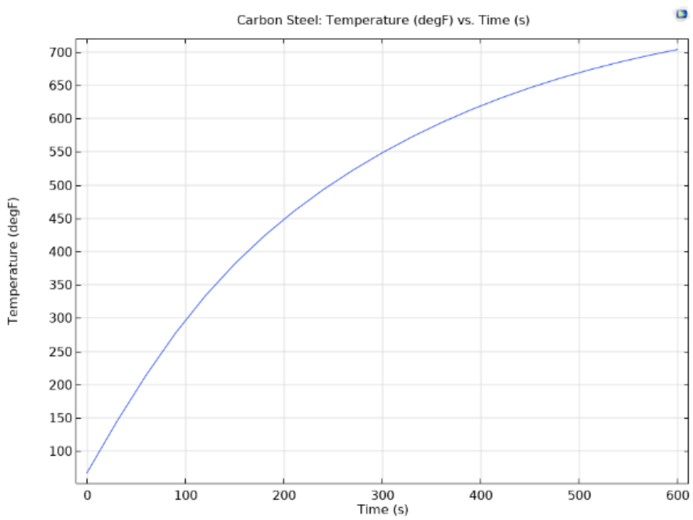
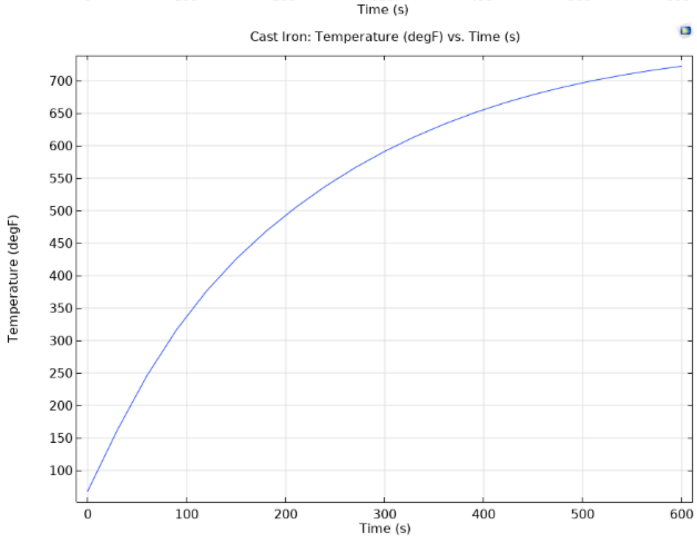


Figure 15. Von Mises thermal stress for the cast-iron pan at 30seconds. (Low thermal stress at base, high thermal stress at handle to body connection)
Figure 16: Von Mises thermal stress for the cast-iron pan at 600 seconds. (Low thermal stress at base, high thermal stress at handle to body connection)

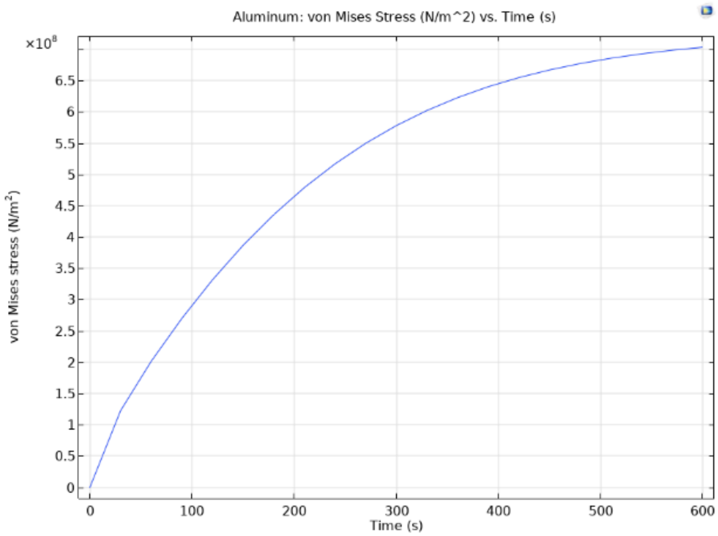
Temperature vs. Time Graphs

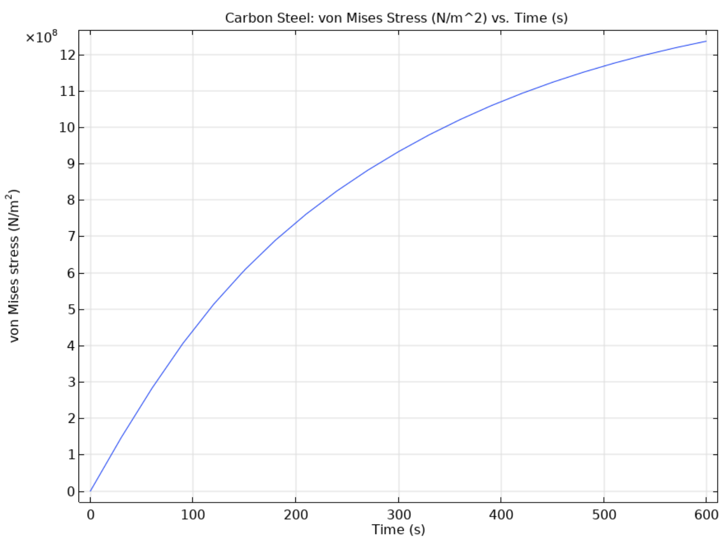


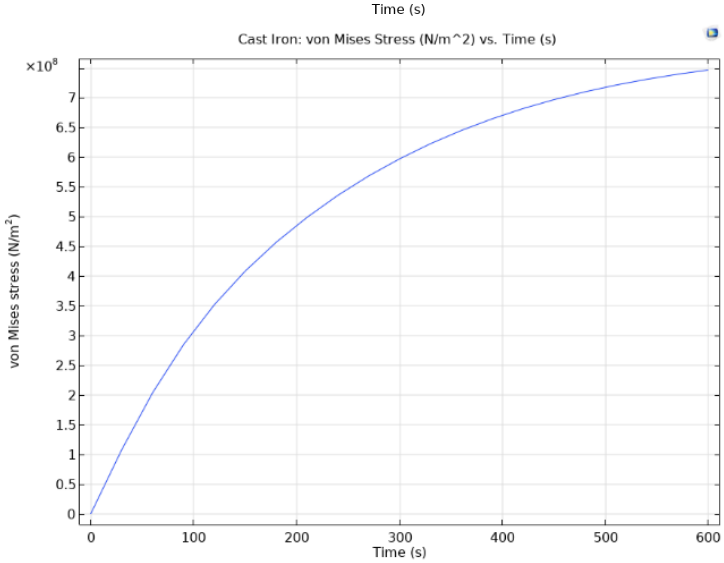




von Mises Stress vs. Time Graphs.







Displacement vs. Time Graphs

No graphs because displacement does not occur at the center point.

DISCUSSION

Model Assumptions and Stress Interpretation

The von Mises stress values predicted by the COMSOL model increase to levels that exceed typical yield strengths for cookware materials. This occurs because the simulation assumes purely linear elastic behavior and therefore does not capture plastic yielding, stress relaxation, or fracture. Under these assumptions, thermally induced stresses continue to accumulate toward the theoretical thermoelastic upper bound when expansion is constrained. In contrast, hand calculations based on classical thermoelastic relations provide order-of-magnitude stress estimates consistent with realistic material behavior, where stresses are limited by yielding and redistribution. A fully realistic prediction of absolute stress magnitudes would require the inclusion of elastoplastic material behavior, temperature-dependent properties, and contact mechanics at the pan–stove interface to allow yielding and stress relaxation. These effects were outside the scope of the present study and the available COMSOL configuration for this course. As a result, the simulated stress values are interpreted as upper-bound elastic stresses used to identify stress localization and relative material performance, rather than as direct predictions of failure stress.

Thermal Behavior

The plots show clear differences in how the three materials conduct and retain heat. Aluminum exhibits the fastest rate of heating and the most uniform temperature distribution across the pan surface. This behavior aligns with aluminum's high thermal conductivity. In contrast, carbon steel and cast-iron show significant non-uniformity, with hotter regions near the base and cooler regions toward the rim and handle. Although aluminum heats up the quickest, it reaches the lowest steady-state temperature of the three materials, leveling off at approximately 550 °F, while carbon steel and cast-iron reach higher maximum temperatures of about 710–720 °F and 720–740 °F, respectively, under identical boundary conditions. After 600 seconds, the minimum temperature in carbon steel is approximately 100 °F, whereas cast iron reaches a higher minimum temperature of around 200 °F, reflecting its strong heat-retention characteristics.

Thermal Stress Distribution

The von Mises stress values predicted by the COMSOL model increase to levels that exceed typical yield strengths for cookware materials. This occurs because the simulation assumes purely linear elastic behavior and does not account for plastic deformation, stress relaxation, or fracture. As a result, the reported stress magnitudes represent upper-bound elastic stress rather than realistic failure stresses. The results are therefore interpreted comparatively to evaluate stress distribution trends, localization, and relative material performance under identical heating conditions. The thermal stress plots demonstrate a strong increase in von Mises stress over time as temperatures rise. Aluminum develops stresses ranging from 0 to approximately 250 MPa at 30 seconds, increasing to a maximum range of about 500–2500 MPa by 600 seconds. Carbon steel shows stress magnitudes between 0 and roughly 140 MPa at 30 seconds, growing to approximately 200–1200 MPa at 600 seconds. Cast iron experiences the lowest stress initially (0–120 MPa at 30 seconds), but by 600 seconds it develops stress values in the same numerical range as aluminum (approximately 500–2500 MPa). Carbon steel exhibits the most concentrated and localized thermal stress, particularly near the base and base-to-sidewall transition, while aluminum and cast iron develop larger peak elastic stresses distributed over broader regions at longer heating times.

Thermal Deformation

The thermal deformation results indicate that all three materials undergo small but physically meaningful dimensional changes under gas heating, with maximum displacements on the order of 10^{-4} m. Aluminum exhibits the largest deformation, reaching approximately 1.5×10^{-4} m, which is consistent with its relatively high coefficient of thermal expansion. Carbon steel shows reduced deformation, with a maximum value near 8.5×10^{-5} m, while cast iron displays the smallest deformation at roughly 7.5×10^{-5} m. Despite differences in magnitude, all three materials exhibit a similar spatial deformation pattern, with expansion originating at the heated base and decreasing radially toward the rim. This behavior confirms that deformation is driven primarily by localized thermal gradients rather than uniform temperature rise.

CONCLUSION AND RECOMMENDATIONS

This study successfully modeled thermal distribution, thermal deformation, and thermal stress in cookware using COMSOL Multiphysics. The 3D model created in SolidWorks accurately represents realistic pan geometry, allowing precise simulation of conductive and convective behavior. Among the three materials tested, aluminum provided the most uniform heat distribution and the fastest thermal response. Aluminum developed the lowest thermal stress of the three materials despite undergoing the greatest deformation. Carbon steel showed significant non-uniformity and reached slightly above 700 °F, with lower base stress than cast iron but a noticeable stress concentration at the handle-to-base connection. Cast iron demonstrated strong heat retention, reached approximately 720–740 °F, and produced the highest overall thermal stress, particularly at the handle-to-base connection. The simulation confirms that both material conductivity and geometry influence cooking performance. These findings can guide design improvements in cookware manufacturing, such as optimizing base thickness or incorporating multi-layer materials for better energy efficiency, structural durability, and user safety. The stress-concentration results offer valuable insight for designing cookware that maintains integrity over repeated heating cycles.

ACKNOWLEDGEMENTS

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Dr. Orabi was a great help.

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APPENDIX

A.1 Temperature Rise Calculation

$$T_i = 25°C$$

$$T_f = 100°C$$

$$\Delta T = T_f - T_i$$

$$\Delta T = 75K$$

A.2 Pan Base Volume Determination

$$V = A \cdot t$$

$$A = 0.1195m^2$$

$$V = 0.1195 \times 0.00255$$

$$V = 3.0353 \times 10^{-4}m^3$$

A.3 Mass of Each Material

$$m = \rho \cdot V$$

Aluminum:

$$m = 2700 \times 3.0353 \times 10^{-4} = 0.82kg$$

Carbon Steel:

$$m = 7850 \times 3.0353 \times 10^{-4} = 2.38kg$$

Cast Iron:

$$m = 7200 \times 3.0353 \times 10^{-4} = 2.16kg$$

A.4 Energy Required

$$Q = m \times cp \times \Delta T$$

Aluminum:

$$Q = 0.82 \times 900 \times 75 = 55{,}350J$$

Carbon Steel:

$$Q = 2.38 \times 470 \times 75 = 83{,}895 \text{ J}$$

Cast Iron:

$$Q = 2.16 \times 460 \times 75 = 75{,}210J$$

A.5 Heat Flux

$$q'' = \frac{P}{A}$$

$$P = 750W$$

$$A = 0.0285m^2$$

$$q'' = \frac{750}{0.0285}$$

$$q'' = 26{,}315W/m^2$$

A.6 Temperature Drop Through Thickness

$$\Delta T = \frac{q \times t}{k}$$

$$t = 0.00254m$$

Aluminum:

$$\Delta T = \frac{(26315 \times 0.00254)}{237} = 0.282K$$

Carbon Steel:

$$\Delta T = \frac{(26315 \times 0.00254)}{45} = 1.485K$$

Cast Iron:

$$\Delta T = \frac{(26315 \times 0.00254)}{55} = 1.215K$$

A.7 Effective Heat Flux

$$q''_{eff} = \eta \cdot q''$$

Gas (40%):

$$q''_{eff} = 10{,}526 \frac{W}{m^2}$$

Electric Coil (70%):

$$q''_{eff} = 18{,}421 \frac{W}{m^2}$$

Induction (80%):

$$q''_{eff} = 21{,}052 \frac{W}{m^2}$$

A.8 Heating Time

$$t = \frac{Q}{\eta \times P}$$

Aluminium:

Gas: $55{,}350 / 300 = 184.5\ s$

Electric: $55{,}350 / 525 = 105.43\ s$

$$\text{Induction: } 55{,}350 / 600 = 92.25\ s$$

Carbon Steel:

$$\text{Gas: } 83{,}895 / 300 = 279.65\ s$$

$$\text{Electric: } 83{,}895 / 525 = 159.8\ s$$

$$\text{Induction: } 83{,}895 / 600 = 139.82\ s$$

Cast Iron:

$$\text{Gas: } 75{,}210 / 300 = 250.7\ s$$

$$\text{Electric: } 75{,}210 / 525 = 143.3\ s$$

$$\text{Induction: } 75{,}210 / 600 = 125.35\ s$$

A.9 Thermal Efficiency

Total energy supplied:

$$Esupplied = P \times t$$

$$Esupplied = 750 \times 600 = 450{,}000\ J$$

Efficiency:

$$\eta = Qabsorbed / Esupplied$$

$$Aluminum: \frac{56{,}352}{450{,}000} = 12.3\ \%$$

$$Carbon\ Steel: \frac{83{,}895}{450000} = 18.6\ \%$$

$$Cast\ Iron: \frac{75{,}210}{450000} = 16.7\ \%$$

A.10 Thermal Expansion

$$\Delta L = \alpha \cdot L_0 \times \Delta T$$

(Values shown in Results tables)

A.11 Thermal Stress

$$\sigma = E \cdot \alpha \times \Delta T$$

(Values shown in Results tables)

Table A1 — Material Properties

Property	Aluminum	Cast Iron	Steel
Density (kg/m^3)	**2700**	**7200**	**7850**
Specific heat (J/kg·K)	900	460	470
Conductivity (W/m·K)	237	55	45
CTE (1/K)	23×10^{-6}	11×10^{-6}	12×10^{-6}
Young's Modulus (GPa)	70	100	200
Poisson's Ratio	0.33	0.26	0.29

Table A2 — Hand Calculated Heating Times (s)

Material	Gas	Electric	Induction
Cast Iron	250.7	75,210	125.35
Aluminum	184.5	56,352	92.25
Carbon Steel	279.65	83,895	139.82

Table A3 — Hand Calculated Thermal Efficiency

Material	Absorbed	Efficiency
Cast Iron	75,210	16.7 %
Aluminum	56,352	12.3 %
Carbon Steel	83,895	18.6 %

Table A4 : Hand Calculated Thermal Expansion & Thermal Stress

Material	α (1/K)	E (GPa)	L_0 (m)	ΔT (K)	ΔL (m)	σ = E·α·ΔT (MPa)
Cast Iron	11×10^{-6}	100	0.1905 m	75	**1.5748 *10^-4 m**	**82.5 MPa**
Aluminum	23×10^{-6}	70	0.1905 m	75	**3.2766 *10^-4 m**	**120.8 MPa**
Carbon Steel	12×10^{-6}	200	0.1905 m	75	**1.7145 *10^-4 m**	**180 MPa**

Nomenclature:

Symbol	Description	Units
(P)	Burner power	W (watts)
(t)	Heating time	s (seconds)
($E_{supplied}$)	Total supplied thermal energy (P*t)	J (joules)
(q")	Heat flux applied to pan bottom	W/m²
(A)	Area of pan	m²
(m)	Mass of pan	kg
(c_p)	Specific heat capacity	J/(kg·K)
(ΔT)	Temperature change	K or °C
($Q_{Absorbed}$)	Energy absorbed by pan $mc_p\Delta T$	J
(η)	Thermal efficiency $\eta = \frac{Q_{absorbed}}{E_{supplied}}$	Dimensionless
$\eta_{overall}$	Stove + pan efficiency $\eta_{stove} + \eta_{pan}$	—
T(t)	Temperature of material as a function of time	°C or K
(k)	Thermal conductivity	W/(m·K)
(h)	Convective heat transfer coefficient	W/(m²·K)
(ε)	Surface emissivity	—
(Δ L)	Linear expansion	m or in
(L_0)	Original length	m or in

(α)	Coefficient of thermal expansion	1/K (or µm/m·K)
(Δ T)	Temperature change	K or °C
(r)	Pan radius	m
(τ)	Thickness	m
(V)	Pan material volume	m^3
(ρ)	**Density** **Description**	$\frac{kg}{m^3}$
η_{gas}	Efficiency of gas stove (~0.40)	—
η_{coil}	Efficiency of electric coil (~0.70)	—
$\eta_{induction}$	Efficiency of induction (~0.80)	—