Research Project Final Report

Date: 15 January 2026

University/College: University of Florida

Project Title: The Role of Induction Heating in Microstructure Evolution

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Project End Date: 31 December 2025

    1. Progress on accomplishments vs deliverables:

Task/Deliverable	Progress
Fabricate specimens from as-received steel stock	✓ Completed
Heat treat half the specimens using a conventional box furnace	✓ Completed
Heat treat the other half of the specimens using induction heating	✓ Completed
Metallographically prepare all specimens	✓ Completed
Hardness measurements of all specimens	✓ Completed
Image all specimens using optical microscopy	✓ Completed
Quantitative image analysis	✓ Completed
Data analysis	✓ Completed
Prepare manuscript for a journal publication	60% complete
Lecture developed on heat treatment in the forging industry for use in Miller's Physical Metallurgy course	✓ Completed
Refine lecture on heat treatment in Miller's Physical Metallurgy course	✓ Completed
Prepare final report	✓ Completed

Executive Summary

This research quantifies the differences in recrystallization rates and resultant microstructures of AISI 4130 steel when subjected to conventional radiant heating (RH) versus induction heating (IH). Findings indicate that IH serves as a highly energy-efficient alternative that significantly accelerates recrystallization kinetics and refines grain size compared to RH methods.

Research Motivation

The forging industry is increasingly adopting induction heating (IH) as a primary thermal processing method due to its significant energy efficiency and potential for rapid throughput[1]. Unlike conventional radiant heating, which relies on thermal radiation and convection from an external source, induction heating utilizes resistive heating generated directly within the workpiece via electromagnetic fields.

While the energy-saving benefits of IH are well-documented, the impact of this unique heating mode on the kinetics of microstructural evolution remains insufficiently characterized. Specifically, the rapid heating rates and internal energy generation of IH may fundamentally alter recrystallization behavior, potentially leading to different grain refinement outcomes or mechanical properties compared to traditional furnace-based treatments.

Quantifying these kinetic differences is essential for:

- Predictive Modeling: Developing accurate JMAK parameters (n and K) specifically for induction-based processing.

- Process Optimization: Reducing annealing times effectively without sacrificing microstructural integrity.

- Grain Engineering: Leveraging the potentially higher nucleation rates of IH to achieve superior grain refinement in alloys like AISI 4130 steel.

By systematically comparing IH and RH under controlled deformation conditions, this research aims to provide the foundational data necessary to transition induction heating from a purely energy-saving measure to a precision tool for microstructural control.

Experimental Procedure

To standardize the initial state, all specimens were homogenized and then compressed at room temperature to a 40% height reduction. Samples were then annealed at 700°C for intervals ranging from 1 to 60 minutes using either conventional radiant heating or induction heating. During heating, IH used a 1.1 °C/s heating rate, while RH used a 0.56 °C/s heating rate due to equipment limitations.

The recrystallization fraction, or X, was calculated from the average of 10 Vickers hardness measurements using the following normalization equation.

$$X = 1 - \frac{H - H_u}{H_d - H_u}$$

In this equation, H_u is the mean hardness of the undeformed sample, H_d is the mean hardness of the as-deformed sample, and H is the mean hardness of the recrystallized sample at a given time. The recrystallization kinetics were modeled using the Johnson-Mehl-Avrami-Kolmgorov (JMAK) equation, which was linearized for convenience (as below).
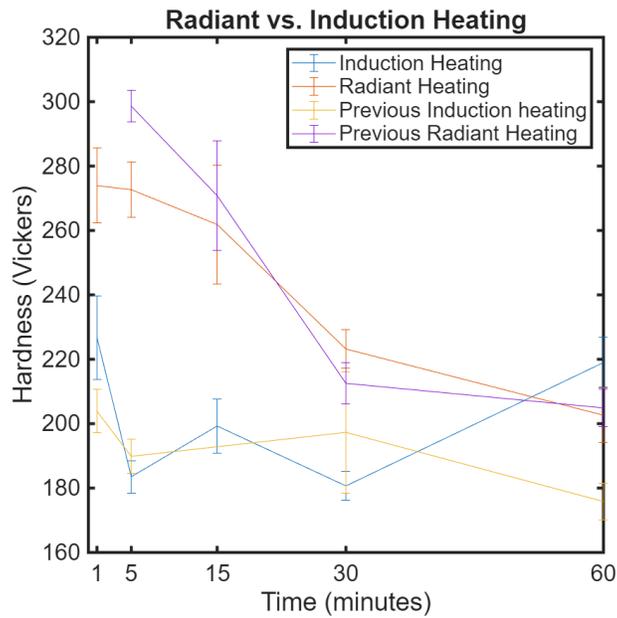
$$X = 1 - e^{-Kt^n} \quad (2)$$

$$\ln\left(\frac{1}{1-X}\right) = Kt^n \quad (3)$$

$$\ln\left(\ln\left(\frac{1}{1-X}\right)\right) = \ln(K) + n\ln(t) \quad (4)$$

In these equations, t is time in minutes, K is the rate constant, and n is the Avrami exponent.

Results

In the plots below, the current results (an average of 3 specimens for each data point) are compared to the previous results (a single data point). As shown, there is some variation in the data, but the key results remain the same.
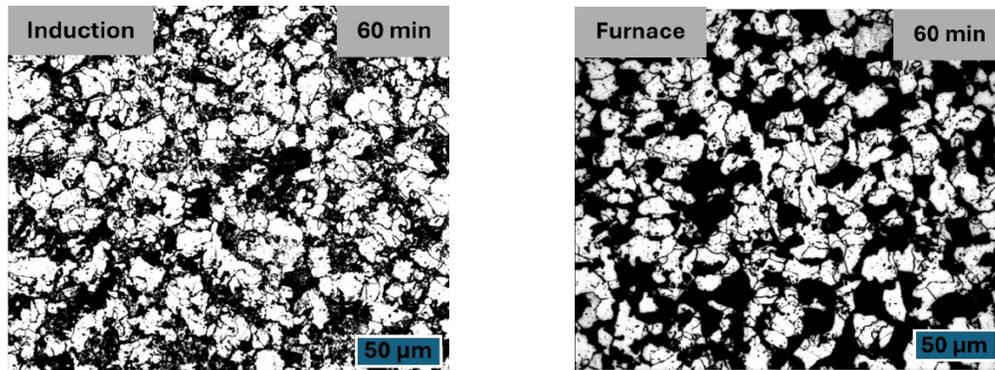

Figure 1: A comparison of Vickers hardness over time in AISI 4130 steel through IH and RH.
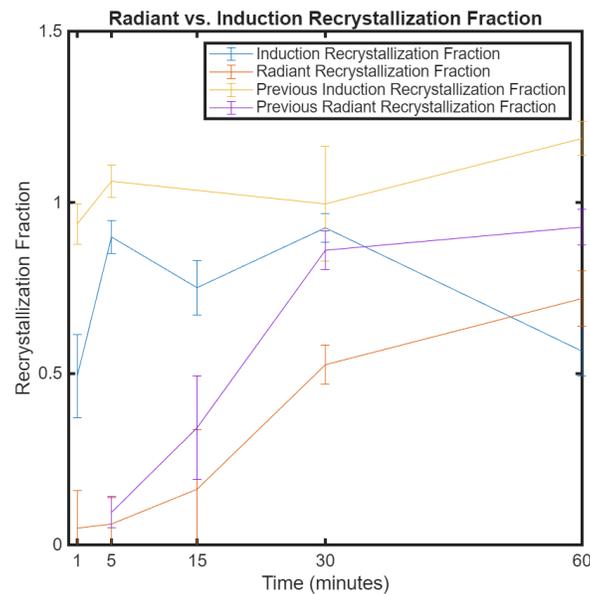
Figure 2: A comparison of the recrystallization fraction over time for radiant and induction heat treatments.
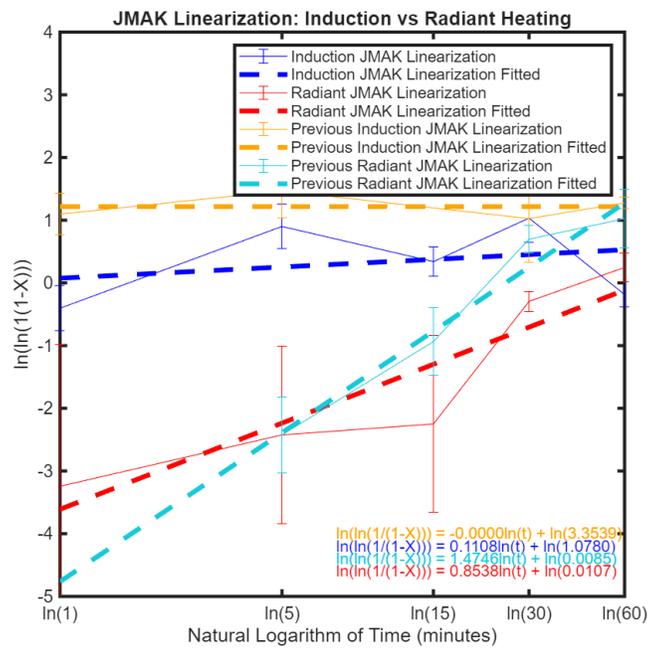
Figure 3: A comparison of JMAK linearization curves

Figure 4: Micrograph comparison after 60 minutes of annealing heat treatment.

Key Findings:

Accelerated Kinetics: The K values for IH are orders of magnitude higher than RH, demonstrating a significantly faster recrystallization rate.

Nucleation Mechanisms: For RH, n values near 1 suggest instantaneous nucleation on grain boundaries followed by one-dimensional growth.

Grain Refinement: IH specimens exhibited an average grain diameter reduction of nearly 2 μm compared to RH. This smaller grain size suggests the higher K value in IH is primarily driven by an increased nucleation rate.

Limitations and Future Directions:

The primary experimental limitation involved the warmup period. Due to the time required to reach 700°C, IH specimens were already >50% recrystallized at t = 0. This led to an artificially low Avrami exponent for IH, which is insufficient to fully characterize IH grain growth stages.

Conclusion:

Induction heating effectively reduces required annealing times and refines the final grain structure of AISI 4130 steel. While experimental design currently obscures the early-stage kinetics of IH, the data clearly supports IH as a superior method for rapid, energy-efficient thermochemical processing.