

# Enhancing Mechanical Performance of Sinter-Forged Fe-Cu Powder Metallurgy Components through Tailored Heat Treatment and Densification Strategies

*A Comparative Study on the Effects of Sinter Forging and Post-Sinter Heat Treatment on Microstructure and Mechanical Properties of Low-Alloy Fe-Cu-C PM Compacts*

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## Abstract

This study presents a process-integrated strategy to enhance the densification and mechanical properties of Fe-Cu-based powder metallurgy (PM) components using sinter forging and tailored heat treatments. A low-alloy Fe-Cu-C premix was compacted to a green density of 7.00 g/cc at 600 Mpa and sintered at  $1120 \pm 5^\circ\text{C}$  in a controlled atmosphere. Post-sinter forging was applied at  $840 \pm 10^\circ\text{C}$  to further density the parts to 7.80 g/cc. Microstructural analysis revealed significant pore closure, grain refinement, and improved bonding, while mechanical testing demonstrated considerable gains in strength and hardness. These results suggest that sinter forging, combined with optimized heat treatment, provides a cost-effective route for fabricating high-density PM parts with superior mechanical properties suitable for demanding structural and load-bearing applications.

**Index Terms**—Powder Metallurgy (PM), Sinter Forging, Densification, Mechanical properties, Heat Treatment, Microstructure Evolution, Green Density.

## I. INTRODUCTION

Powder Metallurgy (PM) has long been recognized as a cost-effective and efficient method for manufacturing complex, near-net-shape components. However, conventionally sintered PM parts often retain residual porosity, which impairs their mechanical strength, particularly in high-load or dynamic environments such as damper systems and structural components.

To address this limitation, advanced densification techniques like Sinter forging have emerged as promising alternatives. Sinter forging integrates thermal diffusion sintering with plastic deformation, resulting in improved microstructural integrity, pore closure, and mechanical reinforcement. This method enhances the strength, hardness, and fatigue resistance of PM parts while maintaining economic and process scalability.

This research investigates the performance of a low-cost Fe-Cu-C alloy system processed through sinter forging, aiming to optimize the mechanical characteristics and densification level through a combined sintering and hot deformation approach. The goal is to demonstrate a robust and scalable solution for manufacturing high-performance PM components.

## II. MATERIALS AND PROCESS METHODOLOGY

### 1. Powder Composition

A Commercially available, low-alloy iron-based premix was selected for the study. The chemical composition was tailored to ensure good compressibility, sintering compatibility, and cost-effectiveness for secondary densification via forging. The formulation is summarized below:

Elements	Content (wt.%)
Iron (Fe)	Balance
Copper (Cu)	1.5%
Carbon (C)	0.65 % (as graphite)
Lubricant	0.30% (Acrawax)

This premix was selected based on its optimal flowability, reduced segregation tendency, and excellent formability, making it suitable for sinter-forging applications. The inclusion of copper enhances diffusion bonding and sintering kinetics, while the controlled carbon level supports matrix hardening during sintering and forging.

## 2. Compaction Process

The powder mixture was compacted uniaxially using a hardened steel die to create cylindrical green slugs. The following parameters were used.

- Part Geometry: Ø80mm, Thickness: 23.5mm,
- Mass of Green Compact: 520 g
- Compaction Pressure: 600mpa
- Green Density Achieved: 7.00 g/cc ( $\pm 0.01$ )

The compaction pressure was optimized to achieve near-theoretical density while preventing lamination or radial cracks. The density was measured using the geometric method with a digital micrometer and analytical weighing scale.

## 3. Sintering Parameters

Sintering was performed in a continuous belt furnace under a controlled reducing atmosphere to enhance diffusion bonding and minimize oxide formation. The process conditions were as follows:

- Sintering Temperature: 1120°C ( $\pm 5^\circ\text{C}$ )
- Sintering Time: 30-40 minutes
- Belt speed: 160 mm/min
- Atmosphere composition: 90% Nitrogen + 10% Hydrogen (dew point  $< -40^\circ\text{C}$ )
- Cooling Method: Forced-air cooling to room temperature

These conditions ensured adequate sintering neck growth, phase transformation of pearlite, and partial densification before forging.

## 4. Forging Procedure:

Post-sintering, the slugs were immediately hot forged to enhance density and reduce porosity through plastic deformation. The key forging parameters were:

- Forging Temperature: 840°C
- Deformation Ratio: ~30% thickness reduction
- Forged Part Geometry: Ø85mm X  $15 \pm 0.05\text{mm}$
- Post-Forging Cooling: Air cooled to ambient temperature

Forging was conducted using a hydraulic press under axial loading. The deformation ratio was controlled to ensure uniform densification without inducing cracks and distortion.

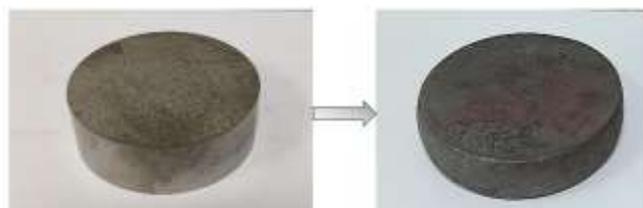
## 5. Density and Dimensional Analysis:

Density was calculated using the Archimedes method (ASTM B962), with the following results:

- Green Density: 6.98 – 7.00 g/cc
- Sintered Density (Pre-forging): 6.97 – 7.00 g/cc
- Final Forged Density: 7.79 – 7.80 g/cc
- Dimensional Reduction: ~8.5mm (from 23.5mm to 15.0mm)

This improvement in density (~11.4% increase) indicates successful pore closure and structural consolidation. The dimensional change aligns with the expected forging strain.

**Figure 1: Illustration of Sintered and Forged slug**



Left – Sintered Slug; Right – Forged Slug

### III. MICROSTRUCTURAL ANALYSIS

The samples were sectioned, ground, polished, and etched using 2% Nital solution for microstructural examination under optical microscopy.

#### Microstructure Images Overview



#### Observations:

- **As sintered:** The microstructure displays interconnected porosity and noticeable copper segregation zones.
- **Sinter-Forged:** Evident grain refinement, improved pore closure, and a more uniform Cu distribution are observed.

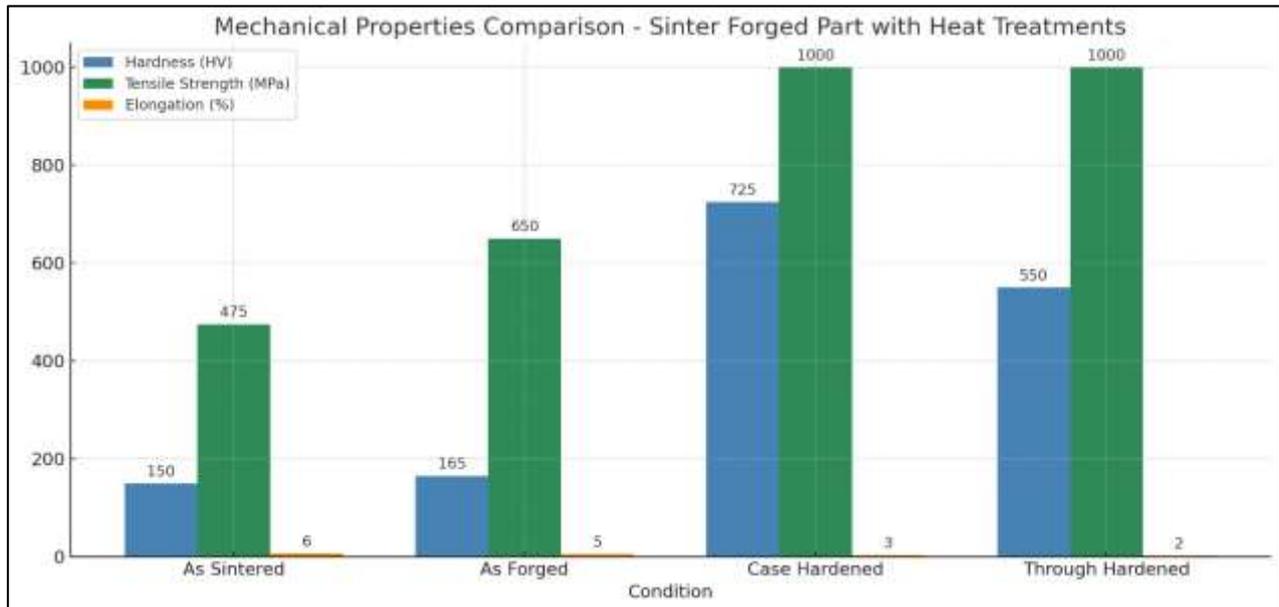
These microstructural transitions indicate significant metallurgical improvements post-forging, promoting better mechanical integrity and stability.

### IV. MECHANICAL TESTING

Standardized mechanical testing was conducted to evaluate enhancements in material strength post-sintering and forging processes.

Property	As Sintered	As Forged	Case Hardened	Through Hardened
Density (g/cc)	7.00	7.80	7.80	7.80
Surface Hardness (HV)	150	165	700-750 (HRC 58-62)	500-600 (HRC 48-54)
Core Hardness (HV)	150	165	340-400 (HRC 35-40)	500-600 (uniform)
Tensile Strength (Mpa)	450-500	600-700	900-1100	950-1050
Yield Strength (Mpa)	-	-	700-900	850-950
Elongation (%)	~6	~5	2-4	1.5-3
Case Depth (mm)	-	-	0.4-0.8 (Effective)	Not Applicable (N/A)
Microstructure	Ferrite + Pearlite	Sherardized Ferrite + Pearlite	Martensite (case) + core	Uniform Martensite

## Graphical Comparison – Mechanical Properties



The bar chart below illustrates the improvement in mechanical parameters across different conditions.

## V. RESULTS AND DISCUSSION

### 5.1 Enhancement in Densification

Forging increased part density from 7.00 g/cc to 7.80 g/cc (~11.4% improvement). This densification minimizes internal voids, enhances mechanical interlocking of grains, and improves load-bearing capabilities. The near-full theoretical density indicates significant advancement in structural performance.

### 5.2 Microstructure Refinement

Forging facilitated:

- Superior diffusion of copper into the iron matrix.
- Strengthening via deformation-induced grain boundary mechanisms.
- Elimination of lamellar and interconnected porosity observed in sintered only parts.

These improvements contribute to superior fatigue resistance and better dimensional stability under mechanical stress.

### 5.3 Mechanical Behavior

The forged parts demonstrated significant improvements in hardness, tensile strength, and yield strength. These enhancements are preliminary attributed to:

- Microstructural homogenization
- Dislocation strengthening mechanisms.
- Transformation to refined ferritic and martensitic phase during heat treatment.

## VI. CONCLUSION

This investigation establishes that a cost-effective Fe-Cu premix, when processed through a controlled sinter forging route, can achieve near-full density levels (up to 7.80 g/cc) and yield mechanical performance comparable to conventionally wrought alloys. The synergistic effect of sintering followed by in-situ hot forging promotes microstructural homogenization, pore closure, and grain boundary densification, significantly enhancing the mechanical integrity of the final component.

**The developed process offers multiple advantages:**

1. Cost effective, utilizing non-exotic alloying elements and commercially available powders.
2. Scalable and industry-compatible, easily integrated into existing sintering and forging lines.
3. Functionally versatile, suitable for high performance applications in automotive, machinery and tooling sectors.

4. Further research should explore post forging thermal treatments, microstructural stability under cyclic loading, and long-term fatigue performance to fully validate the process for industrial deployment.

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