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INVESTIGATION OF THE PRODUCTION AA2024 ALLOY BY THIXOFORGING AND ITS MECHANICAL PROPERTIES

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ABSTRACT

In this study, AA2024 powders were placed into a sintering mold at specified weights and produced using powder metallurgy, followed by thixoforging as a post-processing method. Due to the significant limitation of powder metallurgy - typically resulting in low density and thereby reduced mechanical properties - the powders were compressed at 208 MPa using cold hydraulic pressing. Subsequently, the samples underwent hot solid-state sintering at 500°C for approximately 90 minutes. To further enhance density and mechanical properties, thixoforging was applied post-sintering. Specimens were reheated to 615°C for 45 minutes, then thixoforged in an open die with a 50% plastic deformation rate, and air-cooled. Upon microstructural examination, a heterogeneous structure of large and small grains was observed. The reheating before forging led to partial melting of alloying elements, which concentrated around the α-Al phase, rounding off the microstructural edges and reducing porosity. Density was measured using Archimedes' Principle, while hardness and tensile strength were evaluated across the cross-section. An increase in density from 97,516% to 99,346% was recorded. Furthermore, by averaging the hardness measurements taken across the cross-section, an improvement from 96 HB to 127 HB was observed, representing an approximate 33% increase. Similarly, tensile strength values showed an increase from 220 MPa to 312 MPa, achieving around a 42% enhancement.

Keywords: AA2024, Thixoforging, Mechanical Properties, Powder Metallurgy

1. INTRODUCTION

Aluminum alloys, particularly those in the 2XXX series, have long been integral to aerospace, defense, and automotive applications due to their favorable strength-to-weight ratios, corrosion resistance, and dimensional stability (Ahmed et al., 2023). Among them, the Al–Cu–Mg based 2024 alloy offers a notable combination of high strength, low density, good thermal resistance, and formability. Such properties are commonly enhanced through aging heat treatments that promote

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precipitation hardening, ensuring the material's suitability for demanding structural applications (Shih et al., 1996).

In addition to conventional processing methods, semi-solid metal (SSM) techniques have emerged as effective alternatives for producing near-net shape components with refined microstructures (Tajudin et al., 2023). These techniques rely on developing a non-dendritic, globular grain structure, which imparts thixotropic behavior—allowing the material to flow under shear and regain viscosity when stationary. Early research on developing such thixotropic structures in aluminum alloys, exemplified by the foundational work on the SIMA method, demonstrated that careful control of deformation and reheating parameters can yield improved mechanical characteristics and processability (Bolouri et al., 2011).

Building on these advances, the present study focuses on the AA2024 alloy produced via conventional powder metallurgy and subsequently shaped through thixoforging. By examining the interplay between thixoforging parameters, the aim is to optimize the alloy's microstructural features, relative density properties and mechanical performance. Ultimately, this approach seeks to achieve near-net shape products with superior properties, offering more efficient and high-performance alternatives to traditional manufacturing routes.

2. MATERIALS AND METHODS

In this investigation, AA2024 alloy powders supplied by Seydisehir Aluminum Company (Konya, Turkey) were employed as the primary feedstock. These powders possess an average particle size of 90 μm and are composed of 4.850% Cu, 1.310% Mg, 0.667% Mn, 0.254% Fe, 0.110% Si, 0.079% Zn, 0.033% Cr, and 0.008% Ti, with the remainder being aluminum.

In this investigation, sintering was performed using a cylindrical mold with a 30 mm diameter. A precisely measured mass of 30 g of AA2024 powder, determined with a high-accuracy scale (±0.001 g), was transferred into the mold. The powder was initially consolidated through cold pressing at 15 tons using a hydraulic press. Subsequently, the sintering process was conducted at 500°C under hot-press conditions, applying 40 tons for two and a half hours. Following sintering, the specimens attained dimensions of 30 mm in diameter and 15 mm in height. Prior to thixoforging, the samples were reheated for 45 minutes. A temperature of 615 °C—corresponding to a liquid fraction exceeding 70%—was selected as the processing temperature parameter. Thixoforging was then conducted using an open mold and a hydraulic press exerting a load of 200 tons, achieving a plastic deformation ratio of 50%.

3. CHARACTERIZATION

In this investigation, specimens designated for microstructural examination were first sectioned to the appropriate dimensions and subsequently mounted in cold-setting bakelite. The metallographic preparation involved a series of grinding steps using from 400 to 2000 grit abrasive papers. Polishing was then performed with a SiC suspension, followed by a final polishing stage employing a alumina solution. The preparation was completed by etching the specimens with Keller's reagent. Microstructural observations were initially conducted using a Leica DM4000M optical microscope at a magnification of 50X. Brinell hardness measurements were performed on the cross-sections of the samples using an Innovatest Nemesis 9000 tester, following ISO 6506 guidelines. A 2.5 mm steel indenter and a load of 31.25 kg were applied for 10 seconds, and the average hardness values were recorded. Tensile specimens were prepared in accordance with the DIN EN ISO 6892-1 standard, and tensile testing was conducted using an MTS Criterion Model 45 testing machine. Relative density measurements were additionally recorded utilizing the Archimedean principle.

4. RESULTS AND DISCUSSION

4.1. Relative Density Results

In this study, the influence of thixoforging on enhancing the densification of aluminum alloys produced via powder metallurgy was investigated. Although the initial powder metallurgy processing achieved near-complete densification (~97.5%), residual porosity persisted, a phenomenon frequently noted in the literature for its potential to limit mechanical performance. By reheating the specimens to a semi-solid state (615°C) and applying mechanical pressure during thixoforging, the objective was to increase relative density through the closure of micropores. As a result, relative density could be elevated to approximately 99.346%. This pronounced densification is associated with Arrhenius-based diffusion behavior, underscoring the critical role of temperature in mitigating porosity (Shashikanth & Davidson, 2014). A comparative graph illustrating the as-sintered sample and the thixoforged sample is presented in Figure 1.

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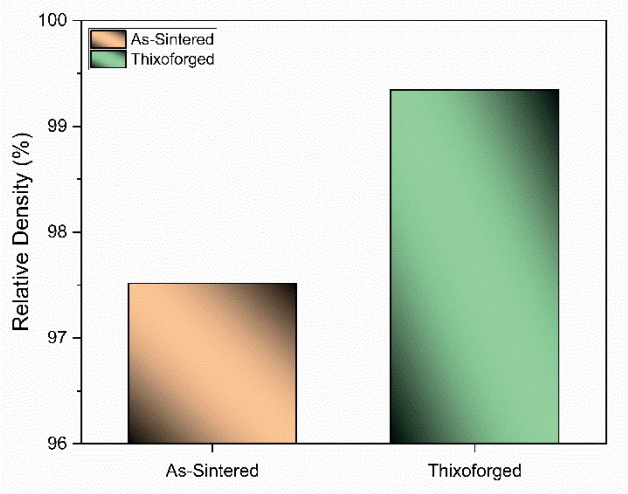


Figure 1. Relative density of samples

4.2. Microstructural Results

ASTM grain size analysis was carried out to determine the percentage-based grain size distribution, and the corresponding average grain sizes are depicted in Figure 2. Microstructural assessment of the as-sintered specimen indicated an average grain size of 22.678 µm. Consistent with common observations in powder metallurgy-derived alloys, micro-porosities were frequently encountered, thereby restricting the material's overall homogeneity and mechanical performance (Parveez et al., 2022). Notably, insufficient grain boundary cohesion facilitates dislocation mobility, weakening the alloy, while the presence of pores accelerates micro-crack initiation and propagation, further undermining mechanical properties. Consequently, the as-sintered specimen demonstrated a relatively modest density of 97.516%.

The thixoforging process markedly improved the porous network by enhancing densification and rearranging the grains, which in turn positively influenced mechanical attributes such as tensile strength. During the reheating phase, the formation of localized liquid phases through solute element dissolution enriched the α-Al phase, effectively enveloping the solid grains (Brollo et al., 2018). Simultaneously, the deformation-induced grain alignment, a hallmark of forging operations, bolstered the alloy's capacity for uniform deformation (Miura et al., 2019). Moreover, increasing thixoforging temperatures led to pronounced grain refinement, reducing the average grain size from 22.678 µm in the as-sintered condition to 11.777 µm in the thixoforged state. In addition, the thixoforged specimen demonstrated relative density of 99.346%.

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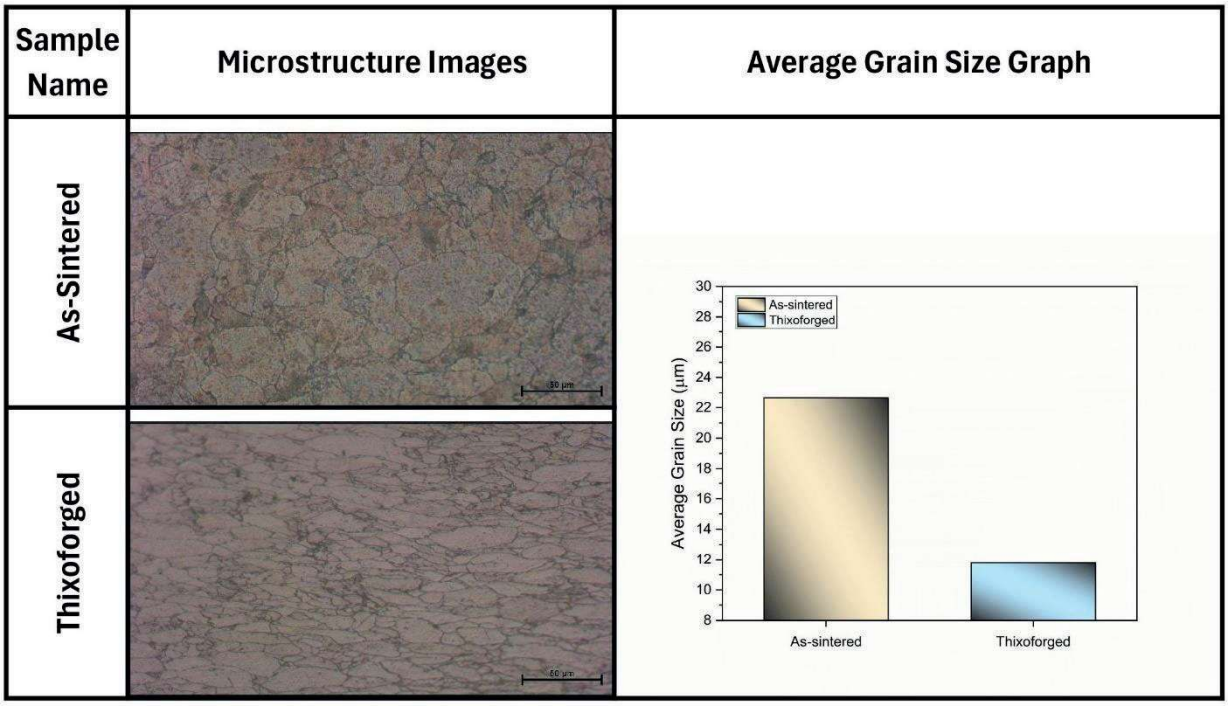


Figure 2. Optical microstructure images and their average grain size graph for both samples

4.3. Mechanical Results

Appropriate cross-sectional segments were prepared from the specimens for subsequent hardness and tensile examinations. During hardness assessments, measurements were systematically acquired across the cross-sectional profile—from the peripheral edge towards the center—and subsequently averaged for each sample. Five measurements were recorded from each region, and their averages and corresponding error factors were subsequently determined. The hardness results are presented graphically in Figure 3. Compared to the as-sintered specimens, which exhibited an average hardness of approximately 95 HB, the thixoforged specimens demonstrated a substantial enhancement, attaining hardness values up to 131 HB.

The improvement in hardness and tensile strength of powder metallurgy-derived aluminum alloys following thixoforging is primarily driven by microstructural refinements and mechanical mechanisms. The application of mechanical pressure in the semi-solid state reduces porosity, leading to a more compact microstructure. This process enhances intergranular bonding and promotes greater material uniformity. Furthermore, during the reheating stage, the liquid phase formed from dissolved solute elements accumulates around the grains, enriching the α-Al phase and strengthening grain

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boundary connections. Additionally, the deformation-induced grain alignment and refinement act to hinder dislocation motion at grain boundaries, thereby significantly increasing hardness (Brollo et al., 2018; Miura et al., 2019).

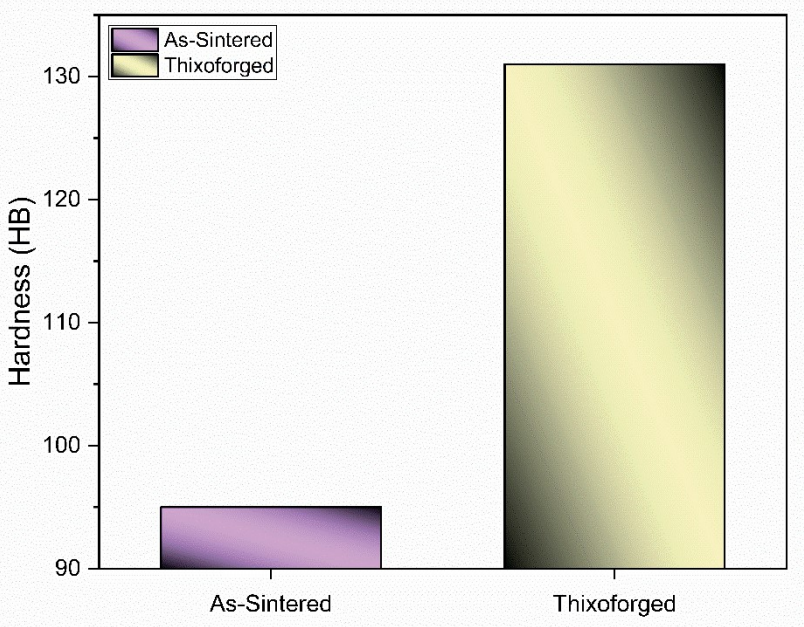


Figure 3. Brinell hardness measurement of samples

The tensile test results, obtained in accordance with the DIN EN ISO 6892-1 standard, are presented graphically in Figure 4. The graph illustrates key mechanical properties, including yield strength, ultimate tensile strength (UTS), and percentage elongation. Following the thixoforging process, the yield strength demonstrated a significant improvement, increasing from 93 MPa in the as-sintered specimen to 127 MPa. Similarly, the UTS showed proportional enhancements, rising from 220 MPa to 312 MPa. Despite the substantial increase in strength, the percentage elongation exhibited a slight decrease. Specifically, the elongation value, which was 17% in the as-sintered specimen, marginally declined to 13% after thixoforging. The relatively modest reduction in elongation can be attributed to the semi-solid state during thixoforging, where deformation occurs under reduced stress levels, minimizing the risk of crack formation. Additionally, with the material reheated to 615°C and containing a liquid phase proportion of at least 60% (accounting for thermal losses during forging), the liquid phase enhances slip activity, facilitating dislocation motion during deformation. The uniform distribution of the liquid phase within the solid matrix alleviates stress concentrations, thereby maintaining ductility to a considerable degree. This balanced phase distribution ensures that elongation values remain stable, avoiding any significant deterioration in material performance (Arif et al., 2023).

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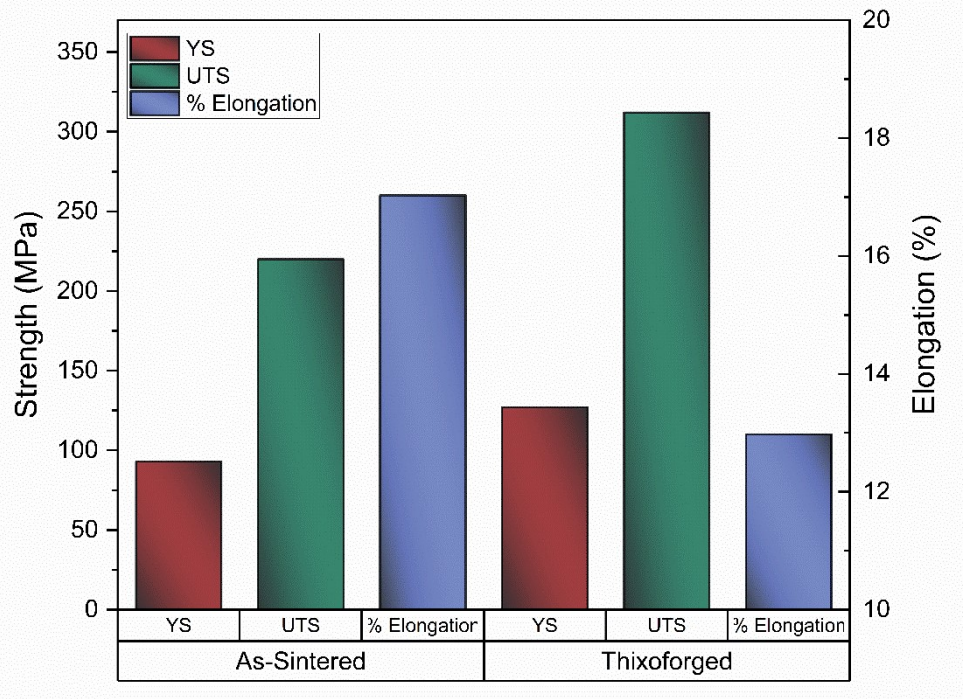


Figure 4. Tensile test results of samples.

5. CONCLUSION

This research highlights the efficacy of thixoforging in enhancing the densification and mechanical characteristics of aluminum alloys fabricated through powder metallurgy. The process effectively minimized residual porosity, increasing the relative density from 97.5% in the as-sintered condition to 99.346% post-thixoforging. Significant microstructural improvements, including grain refinement and alignment, reduced the average grain size from 22.678 µm to 11.777 µm, resulting in improved homogeneity and mechanical performance.

Hardness exhibited a substantial increase, rising from 95 HB to 131 HB, driven by the mitigation of porosity and strain hardening. Tensile properties demonstrated significant enhancements, with yield strength increasing from 93 MPa to 127 MPa and ultimate tensile strength (UTS) from 220 MPa to 312 MPa. Despite these improvements, percentage elongation showed only a minor reduction from 17% to 13%, attributed to the semi-solid state during thixoforging, which enabled uniform deformation through the homogeneous distribution of the liquid phase within the solid matrix.

These findings emphasize thixoforging as an effective post-processing technique for achieving near-complete densification and superior mechanical properties in powder metallurgy-derived aluminum alloys, demonstrating its potential for advanced engineering applications.

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