# Atomic Diffusion Additive Manufacturing: Optimizing Surface Finish and Mechanical Properties of 17-4 PH Stainless Steel through Mass Finishing Techniques

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**Abstract.** Additive manufacturing (AM), commonly referred to as 3D printing, has emerged as a transformative technology within the manufacturing sector, offering distinct advantages such as intricate design capabilities and rapid prototyping. However, the inherent surface roughness and imperfections associated with AM processes necessitate the implementation of effective post-processing techniques to meet industry standards. This paper presents an investigation of the effects of mass finishing processes on metal workpieces fabricated using the Atomic Diffusion Additive Manufacturing (ADAM) process. Various assessments, including tensile strength testing, surface roughness measurement, hardness measurement, and surface topography analysis, were conducted to evaluate the impact of the mass finishing process on the surface finish and mechanical properties of the 3D printed components. The results demonstrate improvements in surface roughness parameters, hardness, and ultimate tensile strength (UTS) following the mass finishing process, with noteworthy observations regarding the effects of prolonged post-processing duration. This research provides valuable insights into optimizing post-processing techniques to enhance the surface quality and mechanical performance of ADAM-produced metal components, thus contributing to the advancement of additive manufacturing.

## Introduction

With advances in Additive Manufacturing (AM) technologies, notably 3D printing, the landscape of metal component production has been profoundly altered, offering unparalleled flexibility in design and the ability to fabricate intricate geometries [1]. Continual technological progression has extended the influence of AM across diverse industries, including automotive, aerospace, architecture, food, and healthcare. By promoting automation, AM technologies—particularly in metal 3D printing methods such as Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Fused Filament Fabrication (FFF)—have reduced the dependence on manual labour, thereby enhancing operational efficiency and productivity. These processes facilitate the creation of complex structures through layer-by-layer fabrication, resulting in components endowed with unique properties [2]. Consequently, the integration of AM technology promises substantial economic advantages for large-scale industries, encompassing cost reduction, enhanced production quality, minimized material wastage, and the production of lighter components with optimized internal geometries. However, the inherent surface roughness, burrs, and irregularities associated with AM processes necessitate effective post-processing methodologies to meet stringent quality criteria and functional prerequisites [1-3].

Various post-processing techniques have been introduced for additively manufactured parts, including machining, heat treatment, wire cutting, grinding, and sandblasting [4-5]. Among these methods, Mass Finishing (MF) stands out as one of the most versatile and widely adopted techniques. Mass finishing, also known as loose abrasive finishing, is a mechanical process utilized for burnishing, deburring, descaling, polishing, and other surface refinement tasks on engineering components, covering a wide spectrum from small-scale to large-scale production. Over recent decades, significant attention has been directed towards MF technology across diverse industries, driven by the pursuit of cost-effective, consistently high-quality, and precisely finished products. Among the most prevalent mass finishing techniques, centrifugal disk finishing has emerged as a prominent choice, offering a high-energy method that serves as a compelling alternative to conventional vibratory processes. This equipment functions by submerging workpieces in a bowl filled with abrasive particles, with the bottom disk of the bowl rotating to induce a rolling motion, causing the workpieces and media to travel along a helical path within the bowl. Consequently, the resulting combination of high pressure and relative movement between the workpieces and media generates an intensive grinding action [6-7].

In conventional metal additive manufacturing technologies, challenges such as the cost of metal powder, availability of alloy compositions, strict powder handling requirements, recycling, and the difficulty of removing powder from components after the build process are prevalent. To address these challenges, metal-based Fused Filament Fabrication (FFF) technology has been developed. This approach involves depositing a composite filament feedstock comprising metal powder and a polymer binder, similar to polymer-type FFF. Notable methods within this category include Atomic Diffusion Additive Manufacturing (ADAM) and Bound Metal Deposition (BMD). Numerous studies have addressed various aspects of AM, such as the dimensional accuracy of printed components, the mechanical behaviour of parts manufactured with different orientations, and the microstructural characterization and porosity analysis of printed specimens [9-10]. However, few research papers have focused on surface finishing and mechanical properties after post-processing. Opoz et al. [5] investigate the impact of diverse post-processing methods—such as machining, polishing, and heat treatment—on the mechanical properties of 3D-printed parts fabricated from 17-4PH stainless steel alloy. Their findings revealed that post-build machining serves to augment both the ultimate tensile strength (UTS) and the isotropy of the material. Furthermore, they demonstrated that centrifugal disk finishing is an efficacious post-process for additive manufacturing. The authors emphasize the need for further investigation in this area.

This study aims to conduct a comprehensive analysis of the impact of centrifugal disk mass finishing on both the mechanical and surface properties of 17-4PH stainless steel tensile samples fabricated using Markforged's MetalX 3D printer. By investigating the post-processing effects on these samples, the research seeks to contribute to the advancement and refinement of additive manufacturing technologies to meet diverse application requirements.

## Experimental Details

**Additive Manufactured Samples Preparation - Markforged's Metal X.** The study employed specimens with parallel-sided central sections to investigate the properties of 17-4PH stainless steel produced using the MetalX system (Fig. 1(a)). Computer-Aided Design (CAD) software (SolidWorks) was used to create the models, which were then exported as stereolithography (STL) files compatible with the Markforged software. Samples were fabricated with 100% infill density, ensuring fully dense material deposition. The dimensions of the samples adhered to the specifications outlined in the British Standard for tensile testing (76.4 mm length × 12 mm width × 4.8 mm thickness) [10]. After the printing process, all samples underwent washing and sintering procedures to dissolve and remove the binding material, thereby consolidating the metal particles into a dense, solid part [11].

**Centrifugal Disc Finishing and Measurements.** In the post-finishing processes, an OTEC CF18 element series centrifugal disc finishing machine (Fig. 1(b)) was employed. For the experimental setup, the machine was filled with 18 litres of conical-shaped plastic media, and the workpieces were carefully positioned within the finishing bowl alongside the media. All samples were polished at a speed of 310 RPM. Each sample group comprised three samples, with the processing time divided into six intervals: 30, 60, 90, 120, 150, and 180 minutes. During the mass-finishing operation, cooling measures were employed to mitigate heat generated by friction, and an anti-foaming solution was used throughout to reduce foaming. After the finishing process, the workpieces were cleaned in an ultrasonic bath to remove any impurities that could potentially affect subsequent measurements. The weight and surface topography of all parts were recorded and measured throughout the tests using a digital scale and scanning electron microscopy (SEM), respectively. Surface roughness measurements were conducted along the sides of the parts (with printing feature patterns) using a Taylor Hobson - Series 1 instrument. Hardness measurements were performed on the internal geometry of the parts using a Mitutoyo HR-400 series with Rockwell Hardness C test conditions. Each measurement was repeated three times for every individual workpiece to ensure reliability.

**Tensile Testing.** A uniaxial tensile test was conducted in accordance with the ASTM E8 standard, using a Tinius Olsen H50 KS tensile testing machine programmed to maintain a constant extension rate of 5 mm/min. Due to the limited dimensions of the specimens, the use of a strain gauge was not feasible; therefore, the extension was carefully recorded for subsequent calculations. After testing, the sample grips, which were assumed to have experienced negligible strain, were removed to provide material for additional analytical investigations.

**(a)**


**(b)**

Fig.1. Diagrams of a Markforged Metal 3D printer (a) and a centrifugal disk finishing machine (b) [11].

## Results and Discussion

Fig. 2(a) illustrates the variations in the average surface roughness (Ra) over different process times. The data show a gradual improvement in surface roughness with increasing process time. The Ra value, initially measured at 2.46 µm for the original unfinished parts, decreased to 2.27 µm. This trend is supported by the Pearson correlation coefficient of approximately 0.98, indicating a strong negative correlation between Ra and process time. Additionally, Fig. 2(b) depicts the change in the weight of the printed parts, revealing a linear relationship between weight losses and processing time, with a Pearson correlation coefficient of 0.98. This finding suggests that as the process time increases, more material is removed from the parts, leading to a reduction in their weight.

The side surface topographies of both the original printed parts and the processed parts were examined using scanning electron microscopy (SEM), as shown in Figure 3. Fig. 3(a) reveals the side surfaces of the original parts with a distinct layer pattern, a characteristic of the additive deposition mechanism employed by ADAM. These parts are built in successive layers of filament material, each approximately 0.1 mm high. The layers exhibit variations in height, resulting in noticeable peaks and valleys. After the mass finishing processes, as illustrated in Fig. 3(c), only the peaks of these layers come into contact with the abrasive media. Consequently, these high points undergo deformation and become flattened, leading to a reduction in the Ra value. This decrease in surface roughness correlates with the smoothing of the peaks and valleys. Fig. 3(b) shows the microstructure of the printed parts at a higher magnification of 20 μm, highlighting the presence of unmelted particles and porosity. After 120 minutes of finishing, the surface morphology has undergone significant transformation due to the abrasive media, including visible scratch marks that indicate material removal. This observation is further supported by the weight loss data shown in Fig. 2(b).

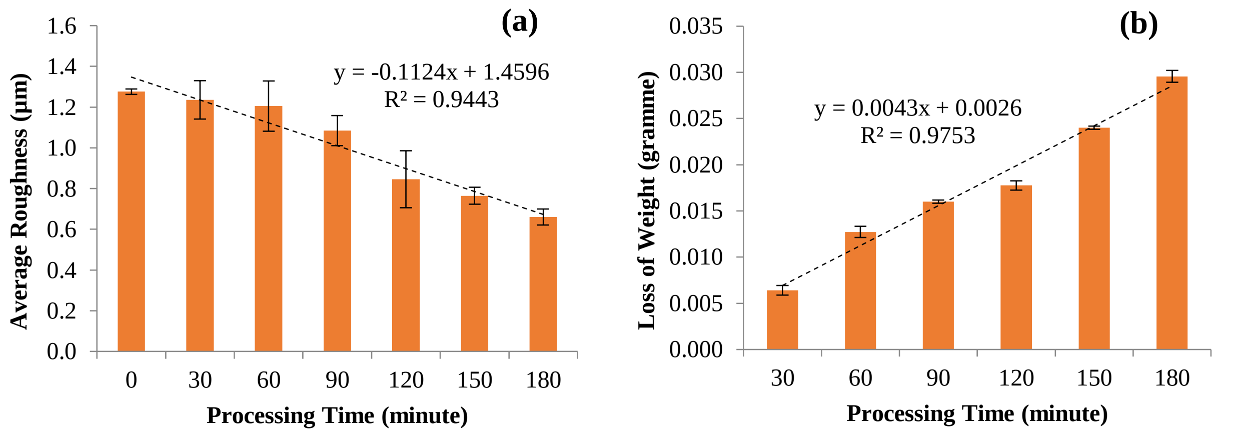


Fig.2. Examples of the surface roughness Ra (a) and loss of weight obtained using for various durations (b)

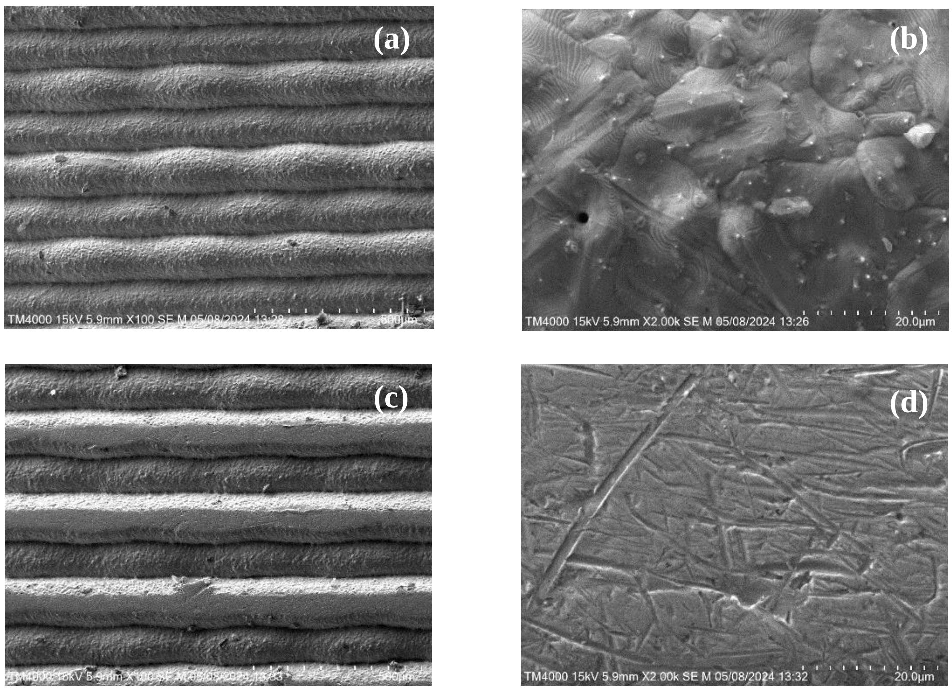


Fig. 3. (a) and (b) typical side surface topographies of as - manufactured ADAM parts. (c) and (d) surface topographies after 120 minutes of processing.

The impact of the mass finishing process on the mechanical properties of the printed parts was thoroughly evaluated. Fig. 4 (a) illustrates the variation in Rockwell hardness at different processing times. Initially, no significant change in hardness was observed within the first 60 minutes of finishing, with the hardness value remaining around 36 HRC, consistent with values reported by Markforged [10]. This initial period is primarily characterized by surface smoothing and material removal. During this phase, the finishing media work to reduce surface roughness and eliminate high points, resulting in a relatively stable hardness value. However, after 60 minutes, a noticeable increase in hardness was recorded, with the Rockwell hardness value rising from 38.59 HRC to 43.46 HRC as processing time extended. This increase in hardness can be attributed to mechanical hardening effects, which are similar to those observed in shot peening processes. The delay in hardness improvement is due to the fact that the initial processing time focuses on smoothing and removing material, which does not significantly affect hardness. As the process continues, the repeated impact and pressure exerted by the abrasive media induce work hardening in the material. This effect becomes more pronounced once the initial phase of surface refinement is completed, leading to enhanced hardness values.

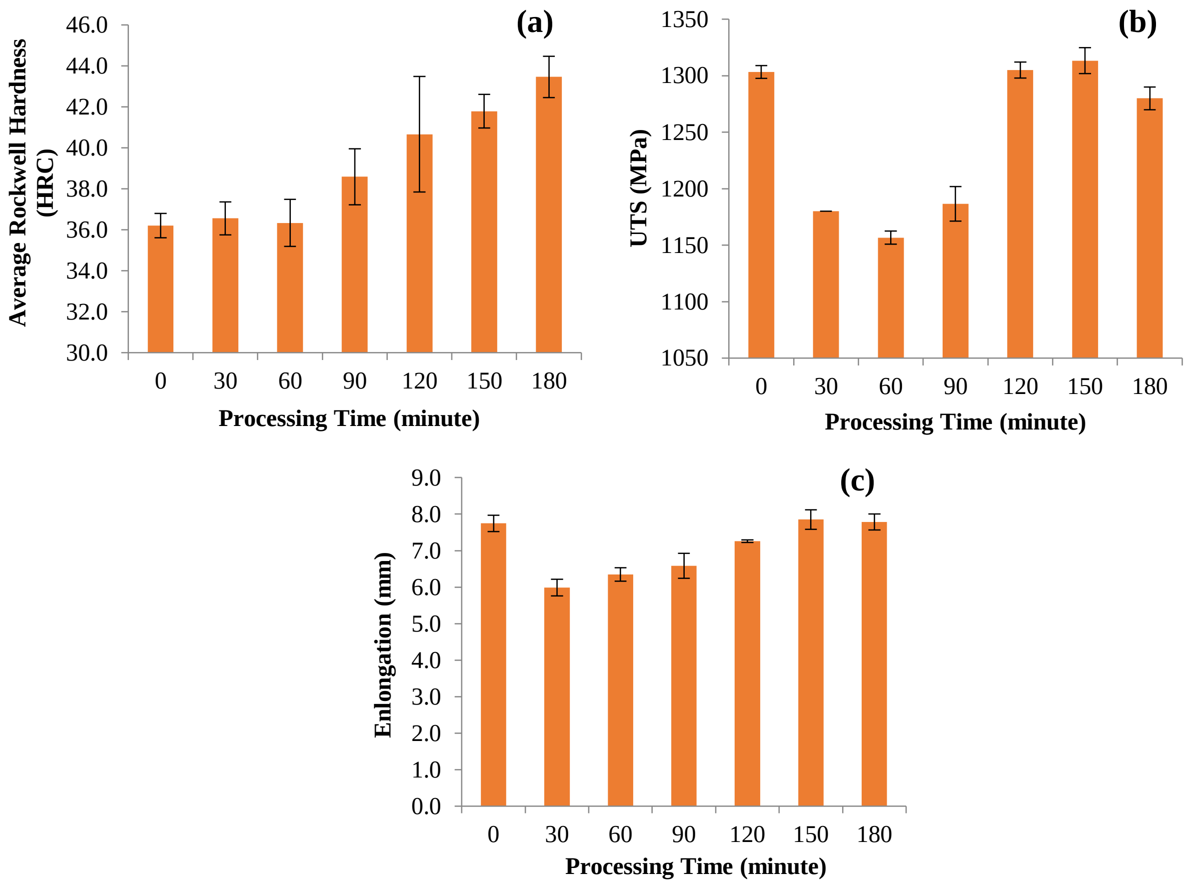


Fig.4. Average Rockwell hardness and mechanical properties recorded from the parts at various process times are shown in the following figures: (a) Rockwell hardness (HRC), (b) Ultimate Tensile Strength (UTS) and (c) Elongation.

Tensile test results, presented in Fig. 4 (b) and (c), further support these findings. For the first 90 minutes of finishing, the ultimate tensile strength (UTS) ranged from 1156 MPa to 1186 MPa. However, with an additional processing time, the UTS increased to approximately 1280 MPa to 1313 MPa. Elongation also improved with longer processing times, indicating enhanced ductility. These results are in line with the findings of Opoz et al. [5], who demonstrated that post-built machining can enhance both UTS and isotropy of 17-4PH stainless steel parts printed by ADAM. They noted that improved surface finish can effectively reduce stress concentrations and increase overall component strength. Additionally, as-printed sintered parts exhibited higher UTS and elongation values compared to the finished parts. This discrepancy may be attributed to potential inconsistencies in the sintering temperature and processing cycle parameters set by Markforged, which requires further investigation.

## Conclusion

This study highlights the significant impact of mass finishing processes on the surface quality and mechanical properties of 3D-printed metal components produced using the Atomic Diffusion Additive Manufacturing (ADAM) method. Comprehensive analyses revealed substantial improvements in surface roughness and morphology due to mass finishing. Specifically, increasing processing time led to a notable reduction in surface roughness, demonstrating the effectiveness of mass finishing in refining the surface quality of the printed parts. Scanning Electron Microscopy (SEM) analysis indicated that the morphology of the parts changed significantly following mass finishing. The observed surface alterations were largely due to the abrasive actions of the finishing media. It is important to note that while plastic media are primarily used for burnishing and polishing, they can indeed induce scratching under certain conditions. Our findings suggest that the scratching effect is associated with the abrasive nature of the media and the intensity of the finishing process. The high-energy contact between the plastic media and the metal surfaces, especially at longer processing times, leads to deformation of the peaks on the surface, which contributes to a reduction in surface roughness. Furthermore, the enhancements in hardness and tensile strength underscore the effectiveness of mass finishing in improving the mechanical properties of the printed components. The results emphasize the crucial role of mass finishing as a practical post-processing technique for optimizing the performance of additive manufactured metal components. Future research should focus on refining process parameters and understanding the mechanisms behind media-induced scratching to better control surface quality and mechanical properties.

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