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Design, Finite Element Analysis, and Experimental Validation of a Jig Holder for SinglecDisc Metallographic Polishing Machines

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Abstract

Specimen stability during metallographic polishing is critical to obtaining accurate microstructural observations, yet inconsistent pressure in single disc polishing machines often causes non-uniform surface finish and unreliable results. While previous studies have extensively addressed polishing parameters and machine performance, limited attention has been given to auxiliary fixtures that actively maintain specimen stability and pressure consistency, a gap this study addresses. This paper proposes a novel jig holder design that integrates finite element-based structural verification with experimental validation, offering a more consistent alternative to conventional manual polishing. The design methodology comprised requirement analysis, three-dimensional CAD modeling, structural simulation via finite element analysis (FEA) to evaluate von Mises stress, displacement, and factor of safety (FOS), followed by fabrication and experimental testing on Aluminum 6061 specimens under polishing loads of 50 g and 150 g, with manual polishing as a baseline. FEA results confirmed the structural safety of the jig holder, with a maximum von Mises stress of 0.103 MPa and a minimum factor of safety of 10. Experimentally, the jig holder consistently produced lower and more uniform surface roughness (0.220–0.225 µm) than manual polishing (0.235 µm), indicating that consistent, controlled pressure distribution rather than operator dependent manual force is the primary mechanism improving surface quality. These findings demonstrate that the proposed jig holder offers a practical, low cost solution for improving specimen preparation reliability in metallographic laboratories, with potential application in quality sensitive materials characterization workflows.

Keywords: Metallographic polishing; Fixture design; Surface roughness; Finite Element Analysis; Specimen holder; Mechanical design

Abstrak

Stabilitas spesimen selama proses pemolesan metalografi sangat penting untuk memperoleh hasil pengamatan struktur mikro yang akurat, namun tekanan yang tidak konsisten pada mesin poles piringan tunggal (*single disc*) sering menyebabkan permukaan tidak seragam dan hasil yang kurang andal. Penelitian-penelitian sebelumnya telah banyak membahas parameter pemolesan dan kinerja mesin, namun perhatian terhadap alat bantu (*fixture*) yang secara aktif menjaga stabilitas spesimen dan konsistensi tekanan masih terbatas celah inilah yang menjadi fokus penelitian ini. Penelitian ini mengusulkan desain jig holder baru yang mengintegrasikan verifikasi struktural berbasis *finite element analysis* (FEA) dengan validasi eksperimental, sebagai alternatif yang lebih konsisten dibandingkan pemolesan manual konvensional. Metodologi desain meliputi analisis kebutuhan, pemodelan tiga dimensi menggunakan CAD, simulasi struktural melalui FEA untuk mengevaluasi tegangan *von mises, displacement, dan factor of safety* (FOS), dilanjutkan dengan proses fabrikasi dan pengujian eksperimental pada spesimen Aluminium 6061 dengan variasi pembebanan 50 g dan 150 g, serta pemolesan manual sebagai pembanding. Hasil FEA mengonfirmasi keamanan struktural jig holder, dengan tegangan von Mises maksimum sebesar 0,103 MPa dan nilai factor of safety minimum sebesar 10. Secara eksperimental, jig holder secara konsisten menghasilkan kekasaran permukaan yang lebih rendah dan lebih seragam (0,220–0,225 µm) dibandingkan pemolesan manual (0,235 µm), yang mengindikasikan bahwa distribusi tekanan yang konsisten dan terkontrol bukan gaya manual yang bergantung pada operator merupakan mekanisme utama peningkatan kualitas permukaan. Temuan ini menunjukkan bahwa jig holder yang diusulkan menawarkan solusi praktis dan berbiaya rendah untuk meningkatkan keandalan preparasi spesimen di laboratorium metalografi, dengan potensi aplikasi pada alur kerja karakterisasi material yang sensitif terhadap kualitas.

Kata kunci: Pemolesan metalografi; Desain fixture; Kekasaran permukaan; Finite Element Analysis; Pemegang spesimen; Desain mekanik

1. Introduction

Metallographic polishing is a critical stage in material characterization because surface quality directly affects the accuracy of microstructural observations [1]. A smooth and defect-free surface is required to ensure reliable analysis of grain structure and phase distribution [2]. In single-disc polishing systems, specimen instability is a common problem that leads to non-uniform material removal and surface defects [3]. Inconsistent pressure during polishing can cause scratches, deformation, and uneven surface finish [4]. These issues reduce the reliability of advanced characterization techniques such as electron backscatter diffraction (EBSD) [5]. Precise control of polishing parameters, including applied force and contact conditions, is essential to achieve high surface integrity [6]. However, conventional polishing processes are still largely dependent on manual operation, which introduces variability and limits repeatability [7]. As a result, operator skill becomes a dominant factor affecting the final surface quality. Several studies have attempted to improve polishing performance through process optimization and advanced systems. The use of compliant tool holders has been shown to improve pressure distribution and polishing consistency [8]. Additive manufacturing has also enabled the fabrication of low-cost, customized polishing tools and fixtures with improved geometric flexibility [9]. However, these approaches share a common limitation, their structural adequacy under actual operating loads is rarely verified prior to fabrication. Most reported fixtures and tool holders are evaluated only through polishing performance outcomes, without accompanying structural analysis to confirm mechanical safety and reliability under load [10]. This represents a scientific gap rather than merely a practical one: the absence of an integrated numerical experimental validation framework for low-cost specimen-holding fixtures in single-disc metallographic polishing [11].

Figure 1. Polishing Machine

The polishing machine developed in this study [12] is shown in Figure 1, its detailed technical specifications are provided in Section 2 (Material and Method). To date, the design of jig holders as a dedicated solution to maintain consistent pressure and minimize specimen movement remains limited [13]. This study addresses this gap by proposing a jig holder whose structural design is verified through finite element analysis (FEA) prior to fabrication, and whose functional performance is subsequently validated through experimental surface roughness measurements against a manual polishing baseline. The novelty of this work lies in this combined FEA and experimental validation approach applied specifically to a simple, low cost mechanical jig holder for single disc metallographic polishing machines. Accordingly, this study aims to (1) design a jig holder capable of maintaining consistent pressure and specimen stability during polishing, (2) verify its structural safety through FEA under representative operating loads, and (3) experimentally evaluate its effect on surface finish quality relative to conventional manual polishing [14].

2. Material and Method

The research workflow, encompassing the stages of design, simulation, fabrication, and experimental evaluation, is illustrated in Figure 2. The single-disc metallographic polishing machine used in this study Figure 1 has overall dimensions of 500 × 700 × 245 mm and is powered by a 135 W electric motor operating at 220 V, equipped with a speed controller capable of reaching up to 600 rpm. Power is transmitted from the motor to the polishing unit through a pulley system consisting of a 100 mm driving pulley and a 300 mm driven pulley.

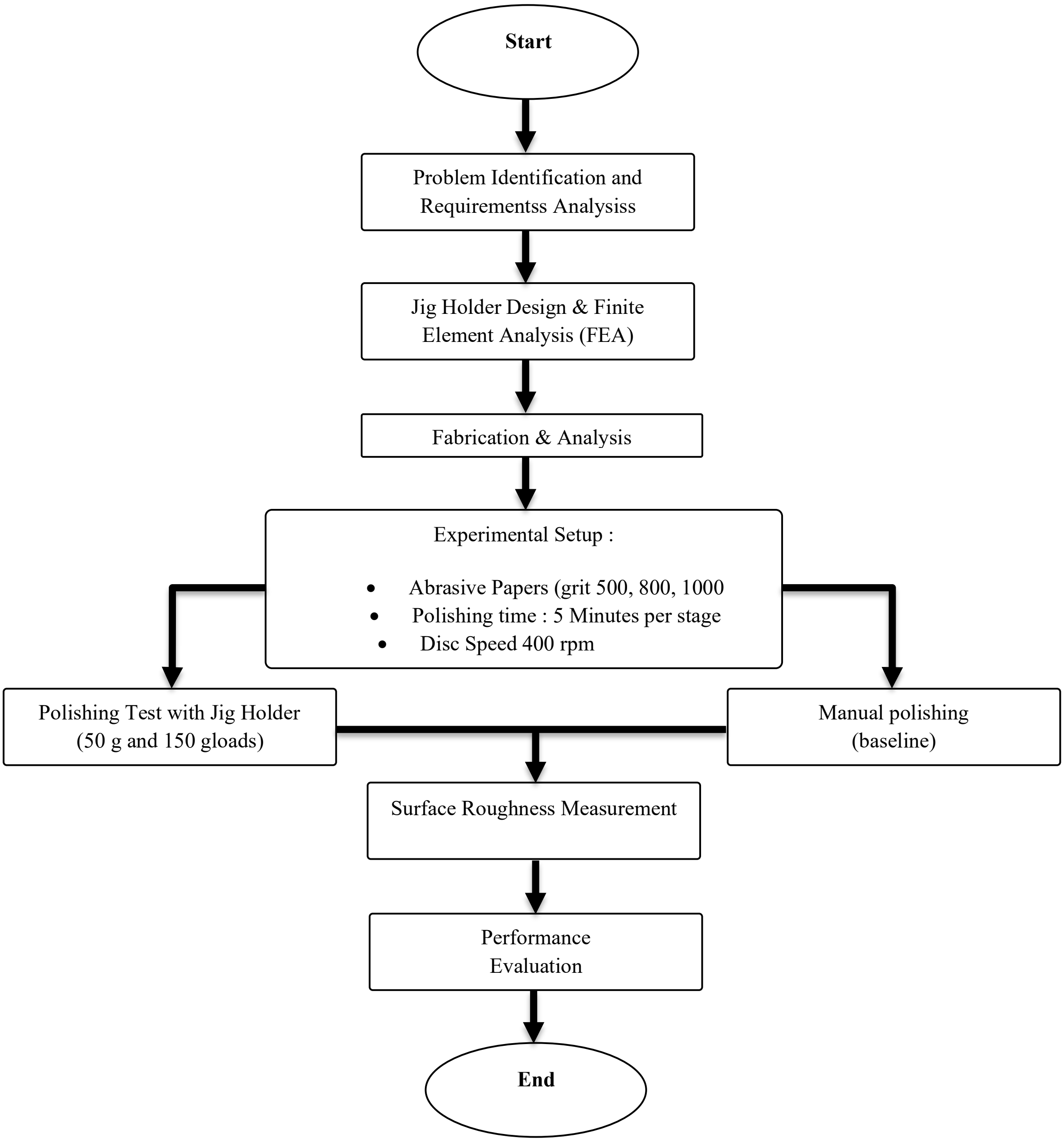


Figure 2. Flow Chart Diagram

The study was initiated through problem identification focusing on specimen instability and inconsistent pressure distribution during metallographic polishing, which are known to significantly affect material removal rate and surface quality [15]. Inadequate control of polishing force and contact conditions may result in surface defects such as scratches, deformation, and non-uniform finishes, ultimately reducing the reliability of microstructural characterization, consistent with earlier observations on manual polishing variability [4]. In addition, unstable specimen positioning during polishing can lead to uneven contact with the polishing disc, further contributing to inconsistent surface quality. To address these issues, a jig holder was designed to enhance specimen stability and maintain consistent pressure during polishing. The design process was carried out using computer-aided design (CAD) to generate a three-dimensional model, with geometric optimization aimed at ensuring structural rigidity, ease of installation, and compatibility with a single-disc polishing machine . The structural performance of the proposed design was then evaluated using finite element analysis (FEA), which is widely applied in engineering design to predict stress distribution and deformation behavior under loading conditions [19]. Simulations were conducted with applied loads of 5 N, 10 N, and 15 N to represent operational conditions, and the analysis focused on von Mises stress, displacement, and factor of safety (FOS) to ensure structural safety and reliability [9]. The FEA loading conditions (5–15 N) were deliberately selected to exceed the actual operational loads applied during subsequent experimental polishing (50 g and 150 g, equivalent to approximately 0.49 N and 1.47 N, respectively) by more than an order of magnitude, representing a conservative overload scenario intended to establish an upper-bound structural safety margin rather than to replicate the exact experimental condition; since the structure remained structurally safe (FOS = 10) even under the highest simulated load of 15 N, its structural integrity under the substantially lower actual operating loads is inherently assured with a considerably larger safety margin.

The simulation was performed in FEA Simulation (static structural analysis) using a solid mesh generated with a blended curvature-based mesher at High mesh quality (16 Jacobian points), with a maximum element size of 16.086 mm and a minimum element size of 0.804 mm. The resulting mesh comprised 58,862 nodes and 32,764 elements; 71.2% of elements had an aspect ratio below 3, only 7.35% exceeded an aspect ratio of 10, and no distorted elements were reported, indicating an overall high-quality discretization. Mesh adequacy was verified through these built in quality metrics (Jacobian ratio and element aspect ratio) rather than a staged h-refinement convergence study. The same mesh settings were applied consistently across the three loading conditions (5 N, 10 N, and 15 N). Three materials were assigned to the assembly based on component function Table 1. The primary load-bearing structural components (base bracket, shaft bracket, clamp holder, mounting bracket, stick holder, mounting lock, bolts, and the calibrated mass weights) were modeled as S45C medium-carbon steel, consistent with the yield strength of 340 MPa used in the safety-factor evaluation. The specimen-holder bearing and specimen jig were modeled as PLA+ (a rigid engineering plastic), reflecting the use of additively manufactured components in these lower-load, non-structural-path parts. The shaft pin was modeled as AISI 304 stainless steel.

Table 1. Polishing Test Parameters

Component(s)	Material	Yield Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m³)
Specimen-holder bearing; specimen jig	PLA+	60	2.5*	0.33	1,230
Base bracket, shaft bracket, clamp holder, mounting bracket, stick holder, mounting lock, bolts, mass weights	S45C steel	340	209	0.269	7,860
Shaft pin	AISI 304	206.8	190	0.29	8,000

Table 2. Polishing Test Parameters

No.	Load Condition	Abrasive Grit 1	Abrasive Grit 2	Abrasive Grit 3	Rotation Speed (rpm)	Time (min)
1	50 g	500	800	1000	400	5
2	150 g	500	800	1000	400	5
3	Manual	500	800	1000	400	5

The detailed polishing parameters used in this study are presented in Table 2. Following numerical validation, the jig holder was fabricated using conventional machining and assembly processes to produce a functional prototype. Experimental testing was performed using abrasive papers with grit sizes of 500, 800, and 1000, with each stage conducted for 5 minutes at a constant rotational speed of 400 rpm, as process parameters are known to influence surface finishing performance [16]. Surface quality was assessed through surface roughness measurements in accordance with ISO 4287 / ISO 21920, which are commonly used as a primary indicator of polishing effectiveness and surface uniformity [17]. For each condition (50 g, 150 g, and manual polishing), one specimen was evaluated, with measurements taken along horizontal and vertical directions to account for directional variability. Additionally, comparative analysis was conducted to evaluate the consistency of surface finish produced under different loading conditions. The results were analyzed to determine the effectiveness of the jig holder in improving specimen stability, ensuring consistent pressure distribution, and enhancing the overall surface finish.

3. Results and Discussion

3.1. Design of the Jig Holder

The jig holder was designed using CAD software and consists of several interconnected components, as illustrated in Figure 3. The names of each component are presented in Table 3.

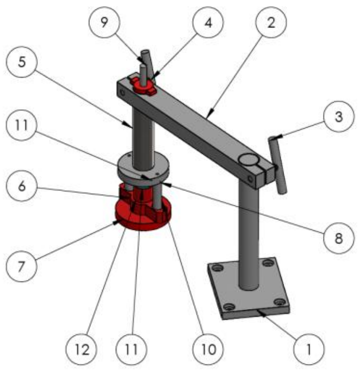


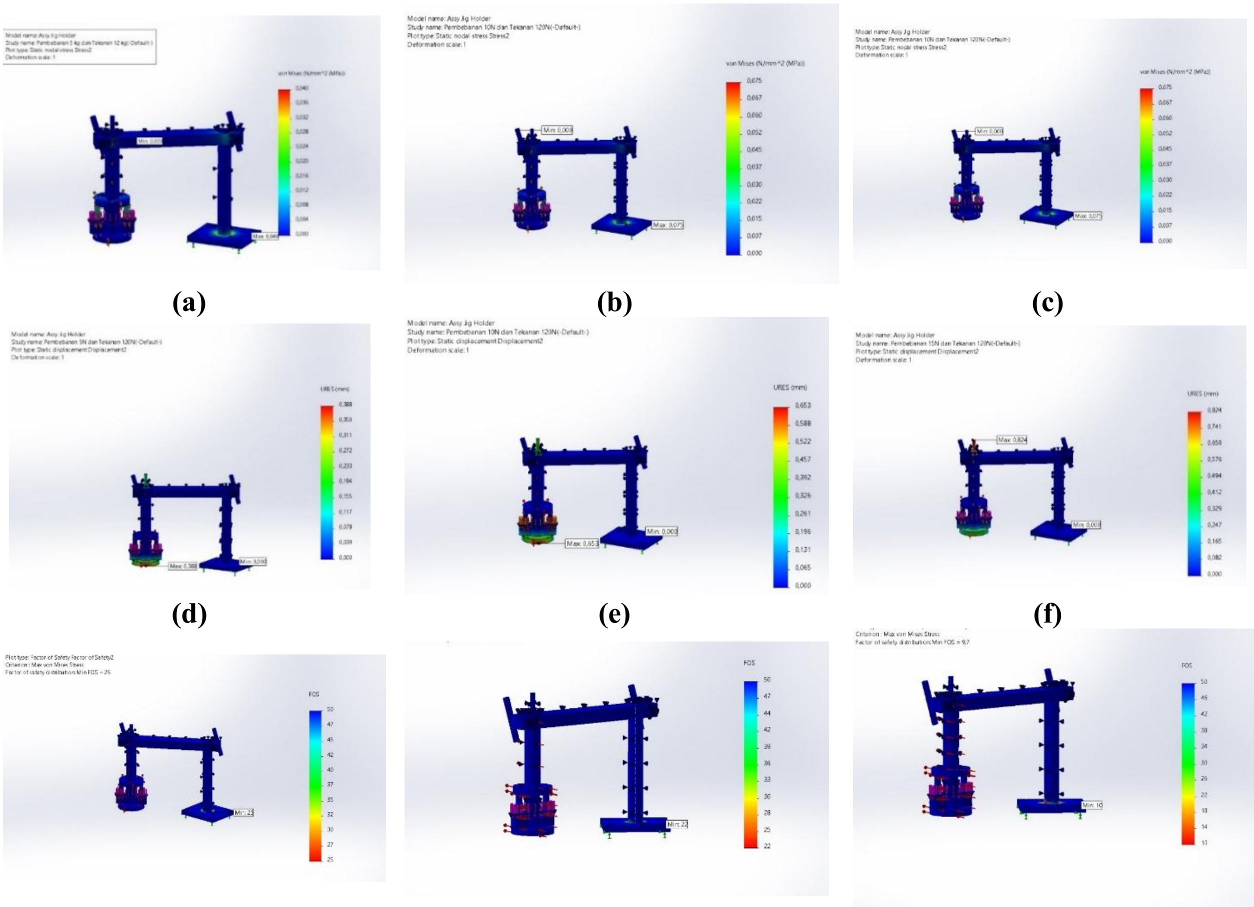
Figure 3. 3D Design of Jig Holder

Table 3. List of Jig Holder Parts

No. Part	Description	No. Part	Description
1	Base Bracket	7	Specimen holder support
2	Mounting Bracket	8	Clamp Holder
3	Mounting Lock	9	M8 × 1.25 shaft
4	Stability of the jig stick	10	Stick Holder
5	Pipe	11	M 50 g
6	Specimen holder	12	M 150 g

3.2. Finite Element Analysis

Mass plays a critical role in influencing the FEA results obtained in this study. The simulation results indicate that increasing the applied load leads to higher von Mises stress and displacement values within the structure. This behavior is consistent with fundamental mechanical principles, where the applied force is directly proportional to mass and acceleration, implying that an increase in mass results in a higher applied load [24]. A comparative analysis was conducted under three loading conditions of 5 N, 10 N, and 15 N, with an additional pressure of 120 N/m². The evaluation focused on key structural parameters, namely von Mises stress, displacement, and factor of safety (FOS), to assess the structural response under varying load conditions as shown in Figure 4.



(a) **(b)** **(c)**

(d) **(e)** **(f)**

(g) **(h)** **(i)**

Figure 4. (a) 5 N von Mises stress, (b) 10 N von Mises stress, (c) 15 N von Mises stress, (d) displacement 5 N, (e) displacement 10 N, (f) displacement 15 N, (g) 5 N FOS, (h) 10 N FOS, and (i) 15 N FOS

The results demonstrate a progressive increase in stress distribution and deformation with increasing load, accompanied by a corresponding decrease in the safety factor. Across all three loading conditions, the maximum von Mises stress consistently occurred at the base bracket, in the region where the vertical support post meets the fixed base plate (Figure 4 a–c) the location of the fixed-geometry constraint. This is consistent with the expected behavior of a cantilevered fixture under a fixed support, where the reaction bending moment, and therefore the stress, is largest at the fixed end rather than at the free loaded end. The minimum factor of safety was found at the same location in all three cases (Figure 4 g–i), confirming that the base-to-post junction is the structurally governing critical region of the design.

The displacement pattern was less uniform at 5 N and 10 N, the maximum resultant displacement occurred at the cantilevered specimen-holder bearing assembly (Figure 4 d-e), whereas at 15 N the maximum shifted to the small protruding stick / handle feature at the top of the vertical post (Figure 4 f). This suggests that, at the highest tested load, the slender handle feature becomes locally more flexible than the specimen-holder assembly, which may reflect its smaller cross-section rather than a change in the overall load path. In all cases, the maximum displacement (0.824 mm at 15 N) remained small relative to the overall dimensions of the jig holder (Figure 1), and is not expected to compromise specimen positioning during polishing.

Table 4. FEA Simulation Results under Different Loading Conditions

Load (N)	Pressure (N/m²)	Maximum Von Mises Stress (MPa)	Maximum Displacement (mm)	Minimum Safety Factor
5	120	0.040	0.388	25
10	120	0.075	0.653	22
15	120	0.103	0.824	10

Based on the results presented in Table 4, loading conditions of 5 N, 10 N, and 15 N under a constant pressure of 120 N/m² produced safety factor (FOS) values of 25, 22, and 10, respectively. The maximum von Mises stress obtained from the simulation was 0.103 MPa, which is significantly lower than the material yield strength of 340 MPa, indicating that the structure remains within the elastic region. In addition, the resulting displacement values are within acceptable limits and do not indicate excessive deformation under the applied loads. These findings are consistent with the behavior reported by [19], who conducted FEA on a manufacturing machine frame and observed that increasing applied load leads to a progressive rise in von Mises stress while the safety factor decreases, yet the structure remains safe as long as the maximum stress stays well below the material's yield strength. Similarly, [20] demonstrated through FEA-based structural analysis of a lifting device that a maximum von Mises stress below 100 MPa and a safety factor exceeding 2.0 are sufficient criteria to confirm structural safety under operational loads, a criterion that the present jig holder design satisfies with considerable margin. Furthermore, a study on FEA of an AL6061 frame structure by [30]. [18] reported that even under the heaviest loading condition, a safety factor above 3 is indicative of a structurally practical and reliable design, reinforcing the validity of the FOS of 10 obtained in this study. According to previous studies, a higher safety factor reflects a greater margin against potential plastic failure, thereby ensuring structural reliability under operational conditions [22][23]. Therefore, the results of the simulation under the highest load of 15 N with a pressure of 120 N/m², yielding an FOS of 10, can be categorized as structurally safe. These findings confirm that the proposed jig holder design does not experience material failure under the given loading conditions [12]. Based on the satisfactory simulation results, the study proceeds to the fabrication stage, which involves machining and assembly processes to produce the physical prototype.

3.3. Eksperimental Testing

Experimental polishing was conducted to evaluate the performance of the jig holder in improving surface finish quality. The specimen material used was Aluminum 6061 with dimensions of 26 mm in length and 19 mm in diameter. The polishing process was performed using a single-disc polishing machine at a constant rotational speed of 400 rpm. Abrasive papers with grit sizes of 500, 800, and 1000 were applied sequentially, with each stage conducted for 5 minutes.

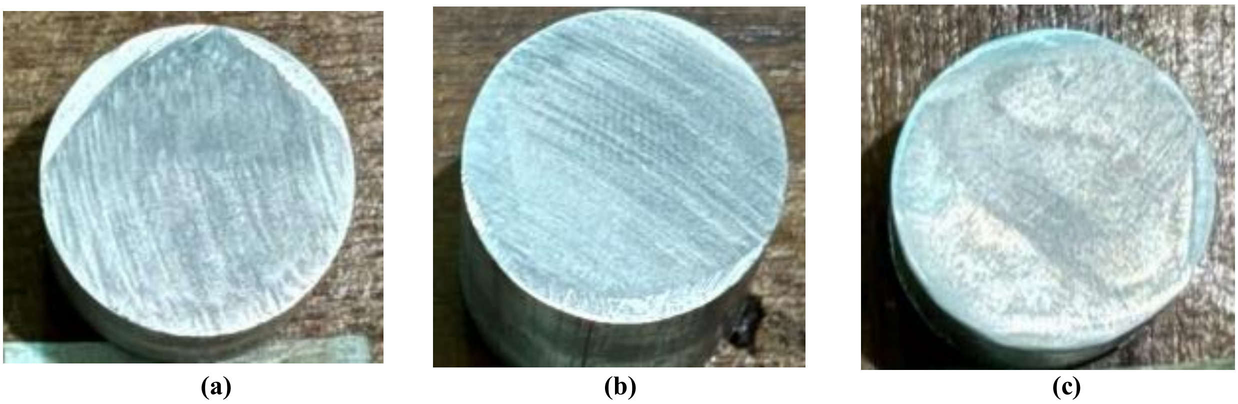


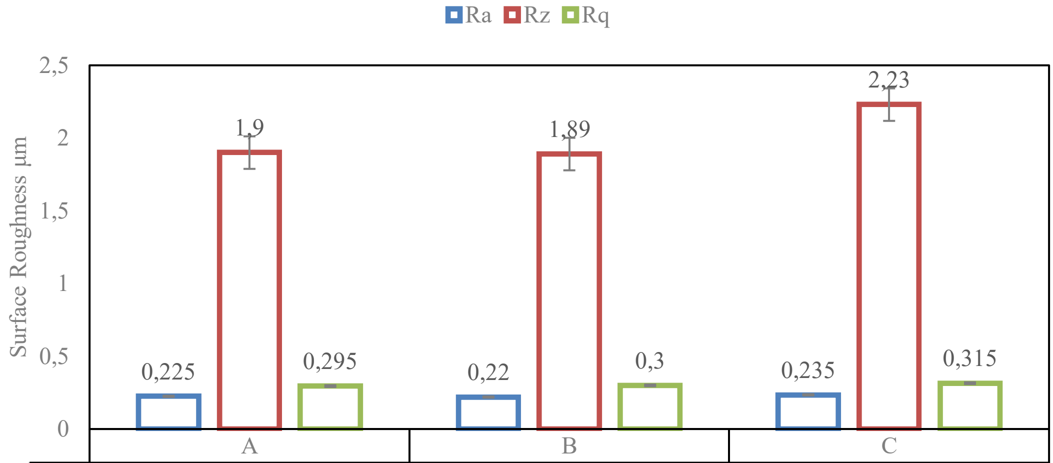
Figure 5. Various sample surface conditions (a) 50 g load, (b) 150 g load, and (c) Manual Polishing

Testing was carried out under two loading conditions of 50 g and 150 g using the jig holder, while manual polishing was performed as a baseline comparison as shown in Figure 5. Surface quality was evaluated by measuring surface roughness, which serves as a key indicator of polishing performance. The results were analyzed comparatively to assess the effectiveness of the jig holder in improving specimen stability and ensuring consistent pressure during the polishing process. Surface roughness testing was conducted on Aluminum 6061 specimens with dimensions of 26 mm in length and 19 mm in diameter at the Integrated Engineering Workshop, BRIN Serpong, Indonesia. The measurement results for all specimens are presented in Table 5.

Table 5. Surface Roughness Measurement Results of Aluminum 6061

Specimen	Condition	Direction	Ra (µm)	Rz (µm)	Rq (µm)
A	50 g (jig holder)	Horizontal	0.14	1.50	0.19
		Vertical	0.31	2.30	0.40
B	150 g (jig holder)	Horizontal	0.23	1.82	0.32
		Vertical	0.21	1.96	0.28
C	Manual polishing	Horizontal	0.28	2.89	0.39
		Vertical	0.19	1.57	0.24

Specimens A and B, polished using the jig holder with loads of 50 g and 150 g, respectively, showed improved surface quality across all roughness parameters. Surface roughness was evaluated using Ra (average roughness), Rz (peak-to-valley height), and Rq (root mean square roughness), providing a comprehensive assessment of surface characteristics. The average values were calculated from horizontal and vertical measurements to ensure representative results. Specimen A (50 g) achieved an average Ra of 0.225 µm, Rz of 1.90 µm, and Rq of 0.295 µm, while specimen B (150 g) produced lower values of Ra 0.22 µm, Rz 1.89 µm, and Rq 0.30 µm, indicating improved surface uniformity at higher loading as shown in Figure 6.



	A	B	C
Ra	0,225	0,22	0,235
Rz	1,9	1,89	2,23
Rq	0,295	0,3	0,315

Figure 6. Comparison of Surface Parameters

In contrast, specimen C (manual polishing) exhibited higher average values of Ra 0.235 µm, Rz 2.23 µm, and Rq 0.315 µm, indicating less stable pressure and increased surface irregularities. These results are consistent with findings reported by [16], who demonstrated that automated mechanical polishing consistently produces lower surface roughness compared to manual hand polishing, primarily due to the elimination of operator variability and more stable contact force. The superiority of mechanically controlled polishing over manual methods was also confirmed by [15], who reported that a guided polishing device with a fixed specimen holder yielded significantly more uniform surface roughness values, whereas manual polishing introduced inconsistencies attributed to variations in operator skill and applied pressure. Additionally, a study on abrasive polishing by [15] established that specimen stability and consistent load application are the primary determinants of surface finish quality, as uncontrolled movement during polishing leads to non-uniform material removal and higher Ra values. The present jig holder effectively addresses this by constraining specimen movement and maintaining steady contact with the polishing disc. Regarding the effect of applied load, higher polishing loads are known to improve surface finish by increasing the contact stress between abrasive and specimen, thereby enhancing material removal efficiency and reducing residual roughness. This is supported by an investigation on semi-fixed abrasive polishing by [17]. In which external load was identified as the most influential parameter on surface roughness and material removal rate, with higher loads yielding smoother surfaces when other parameters are held constant. Increasing the applied load enhances polishing performance by promoting more consistent material removal and stable contact conditions. Overall, all parameters (Ra, Rz, and Rq) consistently demonstrate that the jig holder improves surface finish quality compared to manual polishing, with optimal performance achieved at a load of 150 g. The Ra value of 0.22 µm obtained at 150 g load is notably lower than the 0.2 µm threshold reported in the literature as the critical value above which bacterial adhesion and surface quality degradation become significant, further confirming the effectiveness of the developed jig holder in achieving a high-quality polished surface.

4. Conclusion

This study presents the design and experimental evaluation of a jig holder for a single-disc metallographic polishing machine to improve specimen stability and surface finish quality. The FEA results indicate that the proposed design is structurally safe, with a maximum von Mises stress of 0.103 MPa and a minimum safety factor of 10 under the highest loading condition. Experimental findings demonstrate that the jig holder significantly enhances polishing performance compared to manual polishing. The optimal result was achieved at a load of 150 g, yielding the lowest surface roughness values of Ra = 0.22 µm, Rz = 1.89 µm, and Rq = 0.30 µm. These results confirm that improved pressure consistency and specimen stability contribute to a smoother and more uniform surface finish. Therefore, the developed jig holder provides an effective solution for improving the reliability of metallographic specimen preparation.

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