



Research article

Development of a 13 L Portable Sandblasting System: Design, Fabrication, and Surface Roughness Analysis on Aluminum

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ABSTRACT

Surface preparation plays a vital role in improving coating adhesion and corrosion resistance of metals. Conventional techniques such as sanding or chemical etching are often inefficient, hazardous, or unsuitable for small-scale workshops. Sandblasting provides a more effective solution; however, existing systems are typically bulky and costly. This study aimed to design and evaluate a portable dry sandblasting prototype with a 13 L pressure vessel and maximum operating pressure of 8 bar, developed using the Systematic Engineering Design Method. Aluminum specimens were blasted using silica sand (80 mesh) under varying air pressures (4, 5, and 6 bar) and nozzle distances (10, 15, and 20 cm), with spraying time fixed at 20 seconds. Surface roughness was measured with a Surfcomer Fowler SE1700 (JIS B 0601 standard), and macroscopic observations were performed to assess surface morphology. Results indicated that roughness increased with air pressure and decreased with nozzle distance. The untreated specimen had an Ra of 0.69 μm , rising to 7.92 μm at 6 bar and 10 cm. Several conditions, particularly ≥ 5 bar and ≤ 15 cm, produced Ra values above 5 μm , sufficient to improve coating adhesion. The study confirms the prototype's effectiveness and novelty in combining design and validation, offering a compact, low-cost solution for SMEs and automotive workshops.

1. INTRODUCTION

Surface quality of metallic materials plays a fundamental role in ensuring the performance of engineering components, particularly in relation to coating adhesion, corrosion resistance, and long-term reliability [1]. Contamination such as rust, old paint, oil, or foreign particles tends to reduce the adhesion strength of protective coatings and accelerate material degradation [2]. Improving surface conditions is therefore essential not only for enhancing aesthetics but also for strengthening structural functions and extending service life of metallic products.

Conventional approaches such as manual sanding and chemical treatment are often inadequate. Limitations include low effectiveness, environmental risks, and difficulties in reaching complex geometries [3-6]. The use of chemical cleaning agents even poses significant health hazards due to exposure to volatile organic compounds [6]. These shortcomings highlight the need for alternative methods that are more effective, environmentally friendly, and economically feasible.

Sandblasting provides a solution that effectively addresses these limitations. The process not only removes surface contaminants but also modifies surface topography, thereby improving coating adhesion and subsequent protective treatments [7-9]. Previous studies have demonstrated the significant influence of operational parameters such as abrasive particle size, air pressure, nozzle distance and angle, as well as exposure duration [10-16]. Smaller particles tend to produce smoother surfaces, while higher air pressure increases the aggressiveness of abrasion.

Most prior studies on sandblasting, however, have concentrated on large-scale industrial machines characterized by bulky dimensions and high operational costs [7-9]. Such research emphasizes improvements in material performance, for instance in ASTM A516 Grade 70 steel or titanium alloys for biomedical applications [8,9]. While effective, these machines are not suitable for small-to-medium-sized enterprises (SMEs) and automotive workshops due to space limitations, investment costs, and lack of mobility. Research focusing on portable sandblasting systems remains scarce, particularly studies that simultaneously emphasize design development and performance testing. Experimental works employing silica sand abrasives generally focus on process parameters such as air pressure, nozzle distance, or spraying time [10-14].

Most sandblasting studies have not produced portable prototypes that are ready for field application. Design-oriented studies generally stop at the conceptual stage without experimental validation, while other studies only focus on performance testing without a systematic design process. A number of studies have reported on the design and testing of sandblasting machines. Pambudi et al. [17] developed a sandblasting tool with a closed blasting room that effectively cleans rust on SS400 steel while improving work safety, but their study was limited to functional validation. Aziz et al. [18] designed a sandblasting machine using the VDI 2222 method to increase the cleaning productivity of bushing arm pipes with an emphasis on design efficiency and reduced production costs. Saputra et al. [19] designed a small-scale sandblasting tool based on Autodesk Inventor for SS400 components with a focus on frame strength and operator safety, but its performance evaluation has not been quantitatively linked to surface quality characteristics.

Research by Muhammad Iklil Ulil 'Ilmi et al. [20] shows that variations in abrasive size (80 and 100 mesh) at a pressure of 6 bar significantly affect surface cleaning time. Buhari Muslim and Rahmadianto [21] examined the effect of pressure, time, and distance of iron sand spraying on the hardness and roughness of ST37 steel using the Taguchi method, with optimum hardness conditions at a pressure of 8 bar, a time of 30 seconds, and a distance of 10 cm, resulting in a value of 41.1 Hbw, and optimum roughness conditions at a pressure of 8 bar, time of 90 seconds, and distance of 10 cm with a value of 3.79 μm . Fenoria Putri et al. [22] reported that the combination of a spray angle of 60° and pressure of 5 bar on ST50 steel produced the highest surface roughness of 5.582 μm . This gap reveals the absence of comprehensive studies that integrate the design of a portable sandblasting prototype with experimental evaluation of its performance on aluminum surfaces, which represent widely used lightweight industrial materials. Integration of these two aspects is critical to produce a machine design that is not only technically feasible but also functionally effective. In addition, Hasugian et al. [23] showed that increasing the sandblasting time on 6061 aluminum alloy significantly increased the surface roughness to 6.18 μm , which directly impacted the increase in the

adhesion and hardness of the powder coating layer, confirming the important role of the sandblasting process parameter as a surface pre-treatment stage.

The present study addresses this gap through the design and experimental evaluation of a portable dry sandblasting prototype with a chamber capacity of 13 liters and a maximum working pressure of 8 bar. The design stage emphasizes pressure safety, operator ergonomics, and abrasive efficiency, while the experimental stage focuses on surface roughness testing of aluminum plates using 80-mesh silica sand abrasives. Integration of the design and testing phases provides a novel contribution in the form of a portable sandblasting machine suitable for SMEs, along with a systematic analysis of the relationship between operational parameters and surface quality. These findings are expected to serve as a basis for developing operational standards and technical guidelines for small-scale sandblasting equipment in the future.

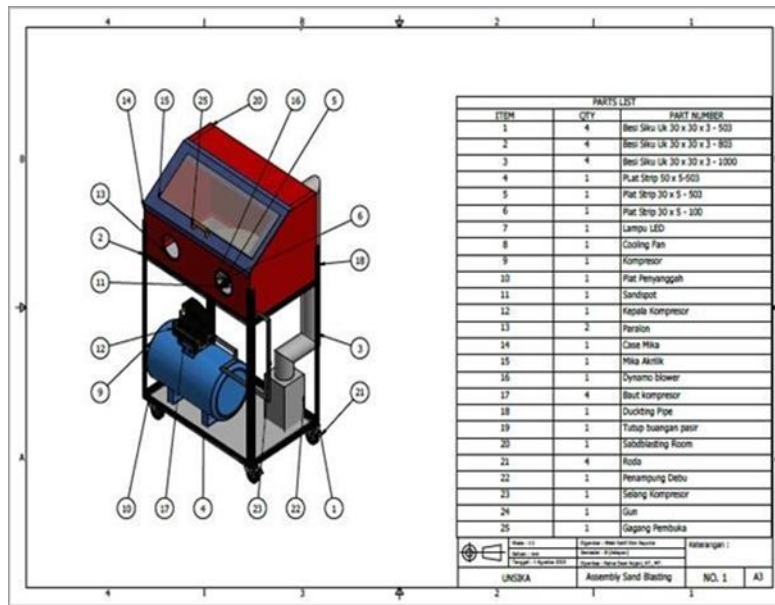


Figure 1. The sandblasting system scheme developed by Saputra et al. [19]

2. Materials and Method

2.1 Prototype Design

The portable sandblasting prototype was developed using the Systematic Engineering Design Method, which emphasizes a structured approach starting from requirement identification, functional formulation, concept generation through morphological matrices, and final design selection using decision matrices. The design process employed CAD software (AutoCAD) and resulted in a prototype with a 13-liter pressure chamber and a maximum working pressure of 8 bar. The system consists of a pressurized vessel, distribution hoses, a ceramic nozzle, and control valves for both air and abrasive flow. Safety against overpressure, operator ergonomics, and efficient abrasive consumption were prioritized during the design process to ensure suitability for small-to-medium-scale industrial applications.

Test Materials

Commercial silica sand with a uniform particle size of 80 mesh was used as the abrasive medium due to its wide availability, relatively low cost, and proven effectiveness in surface cleaning and preparation. Aluminum plates 6061 with dimensions of $50 \times 50 \times 2$ mm were selected as test specimens (Figure 2). Each plate was coated with commercial paint to evaluate the prototype's capability in removing surface coatings. Prior to testing, specimens were cleaned using an organic solvent and compressed air to eliminate dust, oil, and contaminants that could affect the results.



Figure 2. Aluminum test specimens (50 × 50 × 2 mm) coated with commercial paint prior to blasting

2.3 Experimental Variables

The experimental work was designed by varying two main process parameters, namely air pressure and nozzle distance, while maintaining a constant spraying time of 20 seconds. Air pressure was set at three levels (4 bar, 5 bar, and 6 bar) to evaluate the effect of particle kinetic energy on surface roughness. Nozzle distance was also adjusted to three levels (10 cm, 15 cm, and 20 cm) in order to investigate the influence of abrasive particle momentum loss during travel. These variations resulted in a total of nine experimental conditions. For each condition, one aluminum specimen was prepared, and surface roughness was measured at three different points. The mean value from these measurements was considered as the representative roughness (Ra) for that particular condition. Table 1 provides an explanation of the research variables.

Table 1. Experimental specimens and process parameters

Specimen Code	Air Pressure (bar)	Nozzle Distance (cm)
RAW	-	-
P4-D10	4	10
P4-D15	4	15
P4-D20	4	20
P5-D10	5	10
P5-D15	5	15
P5-D20	5	20
P6-D10	6	10
P6-D15	6	15
P6-D20	6	20

2.4 Testing Procedure

Sandblasting was performed according to the defined process parameters. The nozzle was positioned perpendicular (90°) to the specimen surface, and spraying time was controlled using a stopwatch. Each parameter combination was repeated three times to enhance data reliability and minimize variability. After treatment, specimens were dried at room temperature and cleaned with compressed air to remove residual abrasives before surface characterization.

Surface Characterization

Surface roughness was measured using a Surfcoorder Fowler SE1700 with a resolution of $\pm 0.01 \mu\text{m}$, in accordance with the JIS B 0601 standard. Baseline surface roughness values were recorded prior to

sandblasting to determine the magnitude of change induced by the process. After treatment, three measurements were taken from different points on each specimen, with measurement lines oriented parallel to the spraying direction. A cut-off length of 0.8 mm and a sampling length of 4 mm were applied, consistent with standard recommendations. The average value of three measurements was reported as the representative roughness (Ra) of each specimen. Repeated measurements were performed to minimize instrument error.

Macro Structure Imaging Method

Surface images of specimens were taken using a metallographic optical microscope equipped with a digital camera and connected to a computer. Sandblasted aluminum specimens were placed on the microscope stage and focused on the surface area that represented the treatment conditions. Observations were made at a fixed magnification of 50× with controlled lighting from the microscope illumination system. Surface images were recorded directly through the microscope camera and displayed on a computer screen using image acquisition software.

3. RESULT AND DISCUSSION

3.1 Prototype Design and Fabrication

The prototype was developed using the Systematic Engineering Design Method, which systematically addressed design requirements, functional structures, and technical specifications. The resulting system consisted of a 13 L pressurized vessel as the abrasive chamber, a 3 Hp air compressor as the air supply, a sandblasting cabinet measuring 1250 × 900 × 600 mm to provide a safe enclosed workspace, a ceramic nozzle with a 4 mm outlet, abrasive and air hoses, and a pressure regulator with a maximum capacity of 10 bar to stabilize operating conditions.

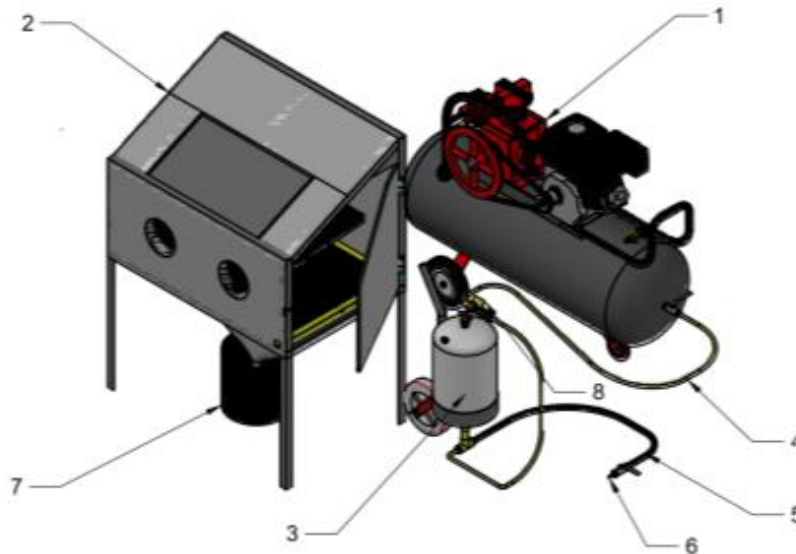


Figure 3. Portable sandblasting prototype

Figure 3. illustrates the conceptual design of the portable sandblasting machine, while Table 1 lists the main components and their specifications. Safety was ensured through the selection of a vessel thickness of 2.3 mm, which can withstand pressures up to 8 bar. Ergonomic considerations were incorporated into the cabinet size and portable configuration, allowing the prototype to be easily operated in small workshops. Efficiency was achieved by applying a direct-feed abrasive delivery system, minimizing abrasive losses while maintaining uniform particle flow to the nozzle.



Figure 4. Fabricated portable sandblasting prototype

The completed prototype is presented in Figure 4, showing the physical arrangement of all components. The final configuration resulted in a compact, portable, and ergonomically operable system, distinguishing it from conventional industrial sandblasting units that are typically bulky, stationary, and cost-intensive. Such portability provides significant advantages for small-to-medium-scale industries, particularly automotive workshops and light manufacturing facilities, where mobility and cost-effectiveness are critical. Detailed specifications of each component are listed in Table 2.

Table 2. Components and specifications of the portable sandblasting prototype

No	Component	Specification	Function
1	Compressor	3 Hp	Provides compressed air supply for abrasive propulsion
2	Sandblasting cabinet	1250 × 900 × 600 mm	Enclosed workspace for operator safety and abrasive containment
3	Pressure vessel	Ø 235 mm, height 360 mm, thickness 2.3 mm	Storage chamber for pressurized abrasive prior to distribution
4	Air hose	Diameter ¼ inch	Transfers compressed air from compressor to the blasting system
5	Abrasive hose	Diameter ¾ inch	Transfers abrasive media from the vessel to the nozzle
6	Nozzle	Ceramic, 4 mm outlet, ball valve control	Directs abrasive-air mixture onto specimen surface
7	Abrasive container	–	Additional reservoir for abrasive supply
8	Pressure regulator	Maximum 10 bar	Maintains and stabilizes operating pressure

3.2 Surface Appearance after Sandblasting

The aluminum specimens initially coated with commercial paint exhibited distinct visual changes after undergoing sandblasting treatment. The abrasive action successfully removed the surface coating, exposing the underlying metallic surface with a uniform matte finish. Surfaces treated at higher air pressures and

shorter nozzle distances displayed more effective and homogeneous coating removal, while those treated at lower pressures and longer distances showed areas of incomplete cleaning and reduced surface texture development.

A representative comparison of specimens under different operating conditions is presented in Figure 5. The images illustrate the gradual transition from partially cleaned surfaces at lower process intensities to fully cleaned and uniformly roughened surfaces at higher pressures and shorter nozzle distances. These observations provide preliminary evidence of the relationship between process parameters and surface modification, which is further quantified in the surface roughness measurements.

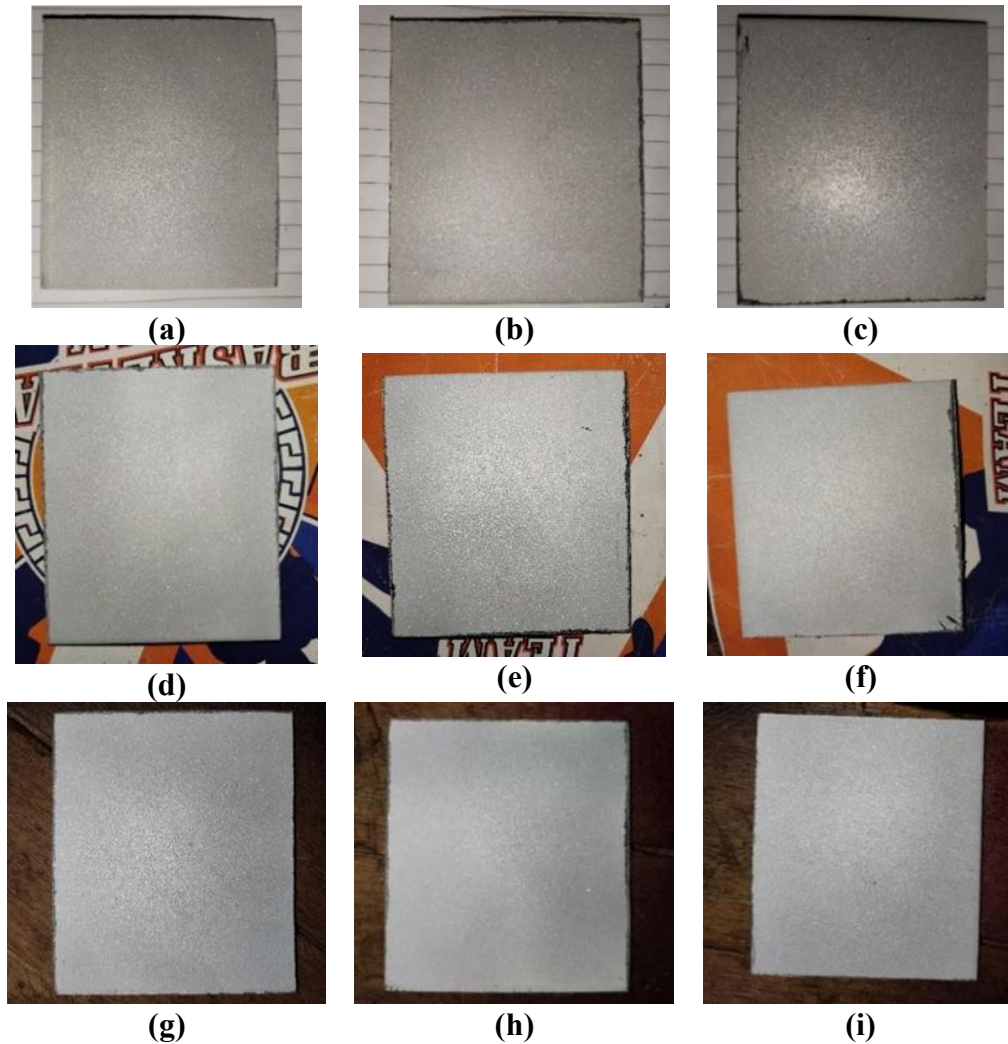


Figure 5. Results of the sandblasting process (a) P4-D10, (b) P4-D15, (c) P4-D20, (d) P5-D10, (e) P5-D15, (f) P5-D20, (g) P6-D10, (h) P6-D15, (i) P6-D20

3.3 Surface Roughness Measurement

Quantitative evaluation of the sandblasted specimens was conducted through surface roughness measurements. The untreated aluminum surface (RM) exhibited an initial average roughness value of $0.69 \mu\text{m}$, representing the baseline condition prior to sandblasting. After treatment, roughness values increased significantly across all experimental conditions, ranging from $3.38 \mu\text{m}$ to $7.92 \mu\text{m}$ depending on the applied process parameters. Table 3 shows a summary of the average roughness (R_a) values obtained from the

specimens at each condition.

Table 3. Summarizes the average roughness (Ra) values obtained from the specimens under each condition.

Specimen Code	Air Pressure (bar)	Nozzle Distance (cm)	Ra (μm)
RAW	–	–	0.69
P4–D10	4	10	4.60
P4–D15	4	15	3.96
P4–D20	4	20	3.38
P5–D10	5	10	6.02
P5–D15	5	15	5.42
P5–D20	5	20	4.96
P6–D10	6	10	7.92
P6–D15	6	15	7.06
P6–D20	6	20	6.21

The results indicate two consistent trends. First, increasing air pressure led to higher surface roughness. For example, specimens treated at 10 cm showed an Ra increase from 4.60 μm (4 bar) to 7.92 μm (6 bar). This outcome can be attributed to the greater kinetic energy of abrasive particles at higher pressures, resulting in more intense surface deformation. Second, increasing nozzle distance reduced roughness values. At 6 bar, roughness decreased from 7.92 μm at 10 cm to 6.21 μm at 20 cm, reflecting the reduction of particle impact momentum due to energy dissipation in air.

These trends are visualized in Figure 6, which presents the relationship between air pressure, nozzle distance, and resulting roughness. The figure clearly illustrates that higher pressures and shorter distances consistently produced rougher surfaces, confirming the strong influence of these parameters on surface morphology.

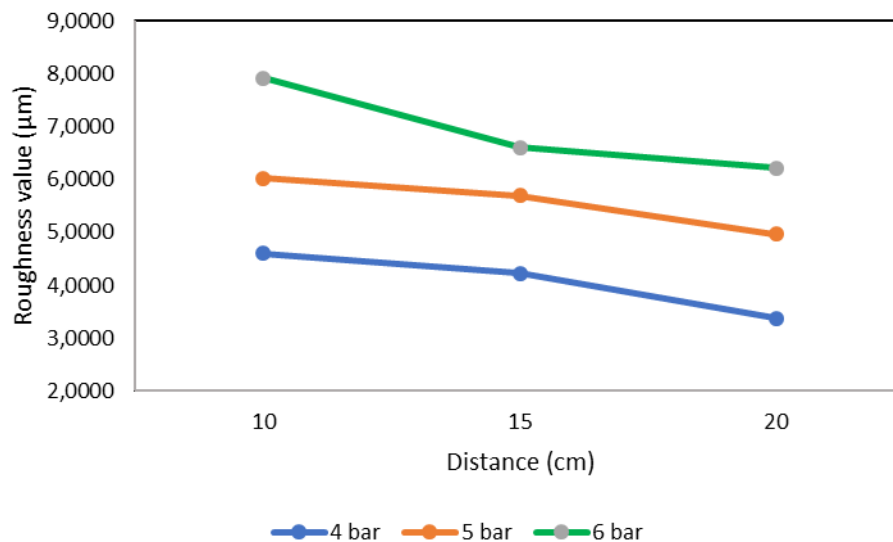


Figure 6. Effect of air pressure and nozzle distance on surface roughness of aluminum specimens

The experimental results clearly demonstrated that both air pressure and nozzle distance strongly affected the surface roughness of aluminum specimens. At a constant nozzle distance of 10 cm, roughness values increased progressively from 4.60 μm at 4 bar to 6.02 μm at 5 bar, and further to 7.92 μm at 6 bar. This trend confirms that higher air pressure accelerates abrasive particles, thereby increasing their kinetic energy

and impact intensity on the surface [10-14]. The resulting micro-cutting and plowing actions deepen the surface profile, leading to greater roughness values.

A consistent but opposite trend was observed for nozzle distance. At the same pressure level, surface roughness decreased as the nozzle was moved further from the specimen. For example, at 6 bar, roughness dropped from 7.92 μm at 10 cm to 7.06 μm at 15 cm, and further to 6.21 μm at 20 cm. The reduction can be attributed to energy dissipation and scattering of abrasive particles during flight, which reduces both velocity and concentration upon impact [12-16]. A longer travel distance also broadens the particle stream, lowering energy density and diminishing the effectiveness of surface texturing.

The interaction between both parameters indicates that the most effective condition was achieved at high pressure combined with short nozzle distance, while the least effective condition occurred at low pressure with long nozzle distance. Specifically, under conditions of 4 bar pressure and a spray distance of 20 cm, this study produced a surface roughness value of 3.38 μm on aluminum material, which is higher than the results of Hasugian et al. [23] of 3.17 μm on 6061 aluminum alloy with the same parameters. These results indicate that the sandblasting tool configuration in this study has a more effective abrasive impact in increasing surface microdeformation.

Under other parameter conditions, the P6–D10 specimen produced the highest surface roughness of 7.92 μm at a pressure of 6 bar and a distance of 10 cm, higher than the results for ST37 steel (3.79 μm) [21] and ST50 steel (5.582 μm) [22]. This difference indicates that the relatively softer nature of aluminum, combined with the tool design and process parameters used, tends to experience greater surface plastic deformation, so that the developed sandblasting tool shows good performance and has the potential to be more effective for cleaning and surface preparation applications.

3.4 Surface Macrostructural Observations

Macroscopic examination of the aluminum specimens provided visual confirmation of the surface modifications induced by sandblasting. The untreated surface appeared relatively smooth, with faint machining marks and no significant irregularities. After blasting, clear morphological changes were observed, characterized by rough grooves, shallow pits, and irregular surface textures. These features became more pronounced with increasing air pressure and decreasing nozzle distance, consistent with the quantitative roughness measurements. At 4 bar, the surface exhibited partial paint removal and limited roughening. The observed grooves were shallow and sparsely distributed, reflecting the relatively low particle velocity and impact energy. Increasing the pressure to 5 bar produced a more uniform matte finish, with clearer abrasive tracks and a denser distribution of surface indentations. At 6 bar, the surface morphology showed deeper grooves, sharper asperities, and widespread plastic deformation, indicating more aggressive cutting and plowing actions of the abrasive particles.

The effect of nozzle distance was also evident in the macroscopic images. At 10 cm, the impact marks appeared dense, sharp, and uniformly distributed, corresponding to the highest Ra values recorded in roughness measurements. As the distance increased to 15 cm and 20 cm, the surface features became less distinct and more widely spaced, reflecting energy dissipation and scattering of abrasive particles during travel. This observation corroborates the quantitative trend that longer nozzle distances reduce effective impact energy and, consequently, surface roughness.

Representative images are shown in Figure 7, which illustrate the progressive evolution of surface morphology from the untreated specimen to those blasted under different operating conditions. These macroscopic observations support the conclusion that sandblasting modifies surfaces primarily through abrasive micro-cutting and plastic deformation mechanisms, whose intensity is governed by air pressure and nozzle distance. The visual evidence strengthens the interpretation of roughness data and highlights the importance of optimizing process parameters to achieve desired surface characteristics.

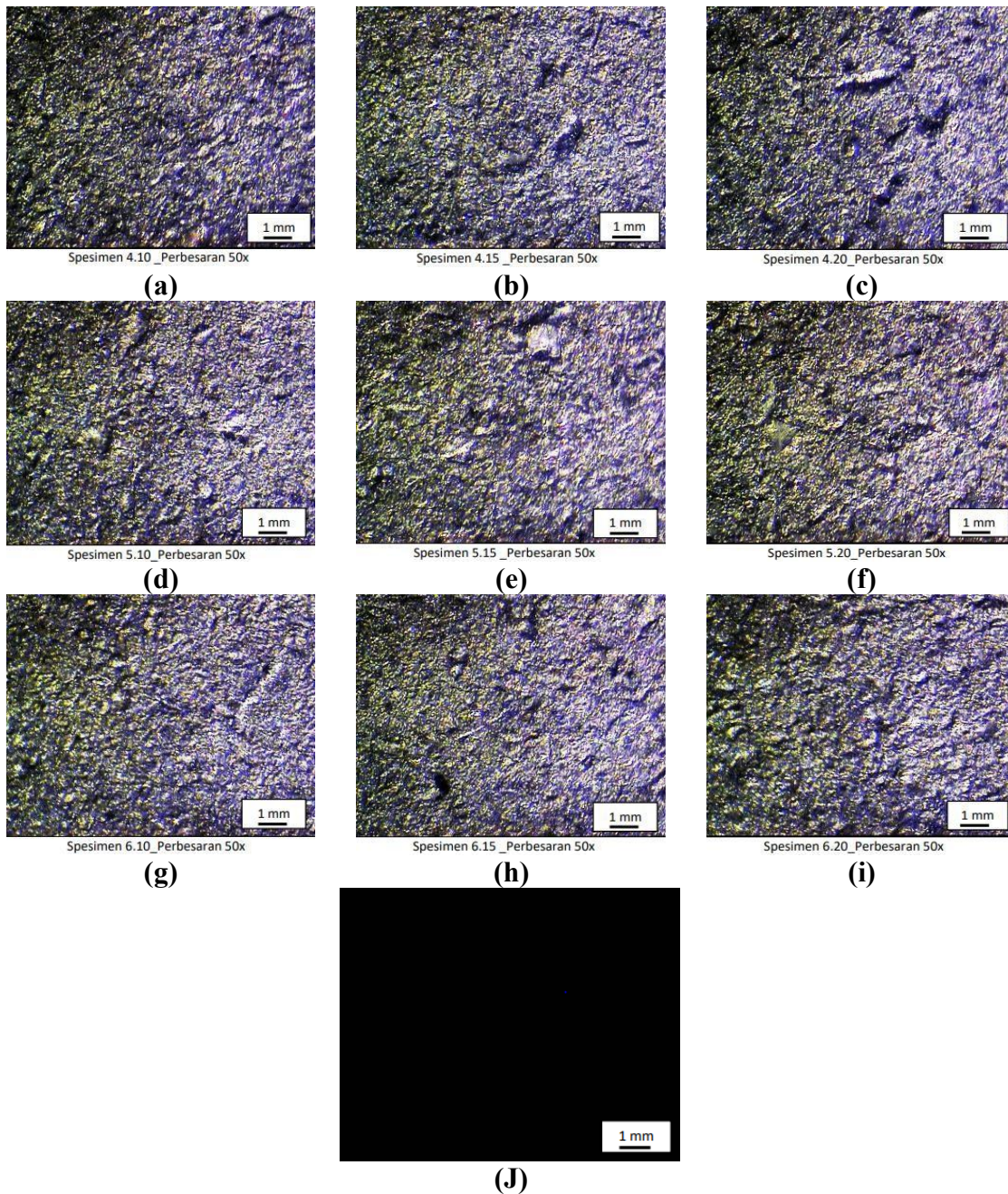


Figure 7. Macroscopic appearance of aluminum surfaces before and after sandblasting under different process conditions, (a) P4-D10, (b) P4-D15, (c) P4-D20, (d) P5-D10, (e) P5-D15, (f) P5-D20, (g) P6-D10, (h) P6-D15, (i) P6-D20, (j) RAW

3.5 Comparative Analysis and Discussion

The results of this study reaffirm the well-established influence of air pressure and nozzle distance as critical process parameters in abrasive blasting. Similar to the findings of Zaroog et al. [8], higher air pressure was found to increase abrasive particle velocity, thereby enhancing impact energy and generating greater surface roughness. Karimi et al. [15] likewise highlighted the role of pressure as the primary

determinant of blasting aggressiveness. The present data corroborate these findings, showing a progressive increase in roughness from 4.60 μm at 4 bar to 7.92 μm at 6 bar at a constant nozzle distance of 10 cm. This consistency strengthens the general consensus that particle velocity, governed by air pressure, is the most influential factor in surface texturing during sandblasting.

While the trends observed are consistent with literature, the magnitude of roughness obtained in this study was notably higher than those reported for harder metallic substrates. Previous studies on carbon steel and titanium alloys under comparable conditions generally reported values in the range of 2–6 μm [7,9], whereas the aluminum specimens in the present study achieved roughness up to 7.92 μm . This discrepancy can be explained by the mechanical properties of aluminum, which has lower hardness and yield strength compared to steel or titanium. The softer substrate facilitates deeper indentation, plastic deformation, and micro-cutting during abrasive impacts, resulting in higher roughness values. These findings highlight the material-dependent nature of blasting outcomes and underscore the need for parameter optimization tailored to specific substrates.

From an application standpoint, surface roughness values exceeding 5 μm are often cited as the threshold for significantly improving coating adhesion strength [2,12]. The prototype developed in this study consistently achieved or surpassed this level under multiple parameter combinations, particularly at pressures ≥ 5 bar and nozzle distances of 10–15 cm. This confirms the system's effectiveness for surface preparation in coating and painting applications. For small-to-medium-sized enterprises (SMEs) and automotive workshops, which often lack access to expensive industrial-scale equipment, the ability of a compact, low-cost prototype to deliver such results offers clear practical value.

The novelty of this research lies in the integration of prototype design and empirical performance evaluation. Prior studies often addressed these aspects separately: design-focused works typically stopped at conceptual or simulated models without experimental validation, while experimental works relied on large industrial blasting units without addressing the design challenges of portability, ergonomics, and cost-effectiveness. By combining these dimensions, the present study contributes both a validated design methodology and empirical performance data, filling a clear research gap in the literature. Furthermore, the identification of an operational window—air pressure between 5–6 bar and nozzle distances of 10–15 cm—provides a practical guideline for achieving optimal surface roughness in aluminum substrates using portable sandblasting systems.

3.6 Limitations and Future Work

Although the prototype demonstrated effective performance in increasing surface roughness on aluminum specimens, several limitations of the study must be acknowledged. First, the experimental evaluation was restricted to a single substrate material (aluminum) and one abrasive type (80-mesh silica sand). The influence of material hardness and abrasive particle size was therefore not investigated, even though these factors are known to strongly affect surface morphology. Second, the process parameters were limited to variations in air pressure and nozzle distance, while other relevant parameters such as nozzle angle, exposure time variation, and abrasive feed rate were not systematically explored. These constraints limit the generalizability of the findings across broader operational conditions.

Furthermore, the prototype evaluation was performed under controlled laboratory conditions, which may not fully represent operational environments in industrial workshops where variables such as operator skill, dust management, and equipment wear play significant roles. Long-term durability of the nozzle, hoses, and pressure chamber also requires further investigation to establish maintenance requirements and cost-effectiveness over extended use.

Future research should address these limitations by conducting multi-material testing (e.g., steel, titanium, and composite substrates) and employing different abrasive types and particle sizes to evaluate the versatility of the prototype. Additional process variables, including nozzle angle, exposure duration, and feed rate, should also be investigated to develop a comprehensive operational window. Beyond laboratory-scale trials, field testing in small-to-medium-scale workshops is recommended to assess practicality, reliability, and user acceptance. Finally, integration of dust collection systems and further

optimization of ergonomic features could enhance both environmental safety and operator comfort, supporting the wider adoption of portable sandblasting technology in real-world applications.

4. CONCLUSION

This study successfully developed and evaluated a portable dry sandblasting prototype with a 13 L pressure vessel and a maximum operating pressure of 8 bar, designed through the Systematic Engineering Design Method. The design emphasized safety, ergonomics, and efficiency, resulting in a compact and portable configuration that is suitable for small-to-medium-scale industrial applications.

Experimental evaluation on aluminum specimens demonstrated that air pressure and nozzle distance are the dominant parameters influencing surface roughness. Higher air pressure consistently increased roughness values, while longer nozzle distances reduced them due to particle energy dissipation and scattering. The untreated specimen had an initial roughness of 0.69 μm , which increased up to 7.92 μm under the most aggressive condition (6 bar, 10 cm). Several parameter combinations, particularly at pressures ≥ 5 bar and nozzle distances of 10–15 cm, produced roughness values above 5 μm , a level widely recognized as enhancing coating adhesion. Macroscopic surface observations provided visual confirmation of these trends, showing progressively deeper grooves, sharper asperities, and denser impact marks with higher pressures and shorter nozzle distances. These findings validate the roughness data and highlight the governing mechanisms of abrasive micro-cutting and plastic deformation.

The comparative analysis showed consistency with previous studies while also revealing that aluminum, due to its lower hardness, achieved higher roughness values compared to steel or titanium alloys under similar conditions. This material-dependent response emphasizes the importance of parameter optimization tailored to specific substrates. The main contribution of this study lies in the integration of design development and empirical validation, which is rarely addressed in prior works. By combining these aspects, the research not only delivers a validated portable sandblasting system but also provides performance data that can serve as the basis for developing operational guidelines and best practices for SMEs and automotive workshops.

Future work should expand the evaluation to multiple substrate materials, different abrasive types and particle sizes, as well as additional process variables such as nozzle angle, exposure time, and feed rate. Field testing in real workshop environments is also recommended to assess long-term durability, operational safety, and user acceptance, thereby advancing the practical adoption of portable sandblasting technology.

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