

Quantitative standardization of sandblasting process parameters for enhanced coating adhesion in industrial applications

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ABSTRACT

Sandblasting is a critical surface preparation technique in automotive and industrial applications, yet the absence of standardized process parameters often leads to inconsistent outcomes. This study investigates the effects of air pressure, spraying distance, abrasive type, and abrasive quantity on the maximum cross-sectional area of carbon steel surfaces subjected to sandblasting. Using the Taguchi experimental design (OA L9) with four factors at three levels, nine parameter combinations were tested, each replicated three times. Non-Destructive Microscopic Testing revealed that air pressure, abrasive type, and spraying distance were the most influential factors. Optimal conditions were achieved at 2 bar pressure, 30 cm spraying distance, and the use of river or silica sand in quantities of 450–650 g, with composition No. 7 (3132) producing the largest and most uniform cross-sectional area (100 μm^2). Signal-to-noise ratio analysis confirmed these findings, supporting the physical observations. The results provide a quantitative foundation for optimizing and standardizing sandblasting parameters, thereby improving coating adhesion quality and reducing variability in industrial applications. Future research will focus on fluid dynamics interpretation to refine jet velocity and particle impact efficiency, as well as exploring environmentally friendly abrasive alternatives.

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1. Introduction

Sandblasting is a widely applied surface treatment technique in the automotive and metal industries, primarily used to remove rust, paint, and other contaminants while preparing substrates for protective coatings. The growing demand for vehicle repainting, driven by accidents, long-term usage, and environmental exposure such as rain and sunlight, has made sandblasting an essential process in automotive refinishing [1]. This method is considered highly effective in cleaning carbon steel surfaces from corrosion, old paint, oil, and other impurities, thereby improving the adhesion of protective coatings [2] [3].

The effectiveness of sandblasting depends on several operational parameters, including air pressure, spraying distance, abrasive type, and abrasive quantity. In practice, however, the selection of these parameters often relies on operator experience rather than standardized guidelines, leading to inconsistent and unpredictable results. Previous studies have predominantly focused on surface roughness or erosion rates, while the quantitative relationship between process parameters and the maximum cross-sectional area of blasted surfaces has received limited attention. This gap in knowledge creates uncertainty in optimizing sandblasting operations, which may compromise coating adhesion and overall material performance [2].

Moreover, improper application of sandblasting can generate negative environmental impacts. The process often produces hazardous waste categorized as B3 (Bahan Berbahaya dan Beracun), which

poses risks to both human health and the environment [4], [5]. The choice of abrasive type and spraying technique can also contribute to air pollution, requiring careful management to minimize ecological damage [6]

The difference between this research with the results of previous research is the use of variations in abrasive materials, namely beach sand and river sand. The method emphasizes a quantitative approach, using Taguchi experimental design, signal-to-noise ratio analysis, and microscopic non-destructive testing cross sectional area data to systematically evaluate the effects of air pressure, spraying distance, abrasive type, and abrasive quantity. This methodological rigor supports the objective of establishing standardized parameters that can be consistently applied in industrial practice, thereby reducing reliance on operator experience. The focus on enhanced coating adhesion directly ties to the goal of optimizing surface preparation so that protective coatings bond more effectively and last longer and ending contribute to environmentally responsible sandblasting practices.

This research focuses on the results of the maximum surface area of carbon iron material in the sandblasting process of the paint surface. This method provides a structured framework for analyzing the effects of air pressure, abrasive type, abrasive quantity, and spraying distance on sandblasting outcomes, thereby reducing variability and improving reproducibility. This research is a development of the results of previous research and is more complete. It is clearly detailed in several related studies.

Sandblasting has been recognized as an effective method for cleaning and profiling metallic surfaces prior to coating, enhancing adhesion and mechanical performance of protective layers [3], [2]. The process involves propelling abrasive particles such as silica sand or steel grit at high velocity, creating a controlled roughness profile that facilitates bonding between the substrate and coating [7], [8]. However, improper parameter selection can lead to environmental and health concerns, as sandblasting generates hazardous waste classified as B3 (Bahan Berbahaya dan Beracun) and contributes to air pollution if not properly managed [4], [5], [6].

The choice of abrasive material significantly influences the outcome of sandblasting. Studies have shown that beach sand, river sand, and silica differ in density and mechanical properties, with silica exhibiting the highest density (3000 kg/m³) compared to river sand (2000 kg/m³) and beach sand (1000 kg/m³) [9]. Beach sand, composed of carbonate grains and biogenic minerals such as foraminifera and shell fragments, demonstrates notable resistance to abrasion and thermal stability, with calorimetric values ranging between 730–830 J/kg°C [10], [11]. River sand, on the other hand, has been reported to possess acceptable mechanical properties, including water content of 4.5–5% and alkaline pH, making it suitable for casting applications [12], [13].

Spraying distance is another critical factor, as variations in nozzle-to-surface spacing (20 cm, 30 cm, 40 cm) directly affect the distribution and impact energy of abrasive particles. Shorter distances generally increase impact intensity, while longer distances reduce penetration but improve uniformity. The amount of abrasive material also plays a role, with higher quantities enhancing cleaning efficiency but potentially increasing waste generation [14][15]

Statistical approaches such as Taguchi's Orthogonal Array (OA L9) design have proven effective in optimizing multi-factor processes, allowing researchers to identify significant parameters and their interactions with minimal experimental runs.[16], [17] [18], [19], [20].

Recent studies have also explored environmentally friendly alternatives to conventional abrasives, such as organic powders derived from walnut shells and orange peels, which demonstrated effective cleaning performance while minimizing ecological impact [21], [22]. These innovations highlight the potential for sustainable sandblasting practices in the future.

The research title “Quantitative Standardization of Sandblasting Process Parameters for Enhanced Coating Adhesion in Industrial Applications” is strongly correlated with this references, as each element of the title is reflected in the cited studies and their findings. Advances prior work by systematically analyzing air pressure, abrasive type, abrasive quantity, and spraying distance to maximize the surface area of carbon steel for improved coating adhesion. Sandblasting is widely recognized for enhancing mechanical bonding of protective layers [2], [3], [7], [8], yet improper parameter selection can increase variability and generate hazardous B3 waste [4], [6]. This research highlights how abrasive density and composition—such as silica’s higher density (3000 kg/m³) compared to river sand (2000 kg/m³) and beach sand (1000 kg/m³) [9], [14] along with nozzle distance and abrasive quantity [15], [16], directly influence cleaning efficiency and reproducibility. Employing Taguchi’s OA L9 design enables efficient optimization of these multi-factor processes [17], [22]. Furthermore, the study acknowledges sustainable alternatives like walnut shell and orange peel abrasives, which reduce ecological impact while maintaining performance [21]. Thus, the work provides a structured framework to standardize parameters, improve adhesion, and support environmentally responsible practices.

2. Method

This study employed the Taguchi method of experimental design to systematically evaluate the effects of four process parameters; air pressure, spraying distance, abrasive type, and abrasive quantity on the maximum cross-sectional area of sandblasted carbon steel surfaces. The Taguchi Orthogonal Array (OA L9) was selected, allowing for efficient experimentation with four factors at three levels each, while minimizing the number of experimental runs required. This design generated nine unique parameter combinations, each tested in triplicate to ensure reproducibility and statistical reliability. This factorial arrangement enabled the identification of both individual factor effects and potential interactions among parameters.

In this study, the experimental design was structured using an Orthogonal Array L9(3⁴), which allows evaluation of four factors at three levels each with minimal experimental runs. The response variable measured was the maximum cross-sectional area of the carbon steel surface (μm²), representing the effectiveness of sandblasting in preparing the substrate for coating adhesion. To ensure reliability, each composition was tested with three replications, and the average values were used for statistical analysis. The four experimental factors and their respective levels were defined as follows: air pressure (1 bar, 1.5 bar, 2 bar), spraying distance (20 cm, 30 cm, 40 cm), abrasive type (beach sand, river sand, silica sand), and abrasive quantity (250 g, 450 g, 650 g). This systematic arrangement provided a balanced framework to analyze the influence of each parameter and their interactions, ensuring that the optimization process was both quantitative and reproducible. By applying this design, the study was able to identify significant factors affecting surface area outcomes and establish standardized guidelines for industrial sandblasting applications.

The test specimens consisted of carbon steel plates AISI 1020, selected for their relevance in automotive and industrial applications. 1 mm thick plate, 50 mm x 50 mm, totalling 34 pieces, which were sanded and then sprayed with red pylox in 3 layers and dried for 2 x 24 hours. Special abrasive materials as shown in Fig. 1, included beach sand (density 1000 kg/m³), river sand (2000 kg/m³), and silica sand (3000 kg/m³), each prepared and sieved to ensure a consistent particle-size distribution. The abrasive mass was measured precisely using a digital balance prior to each trial. explained in the following image.

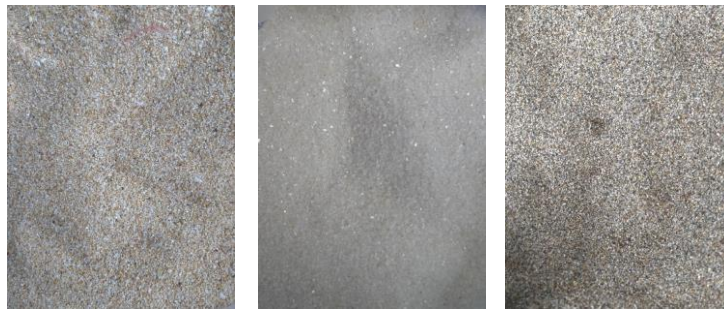


Fig. 1. Materials Abrasive Sandblasting at Beach, Silica, River Sand

The measuring tools used are vernier calipers and (NDT) Non-Destructive Test Microscope. Mitutoyo vernier calipers, particularly the standard Series 530-104, represent precision-engineered measuring instruments designed for durability and accuracy in industrial and laboratory applications. Constructed from hardened stainless steel with a satin chrome finish, they resist rust and provide glare-free readability. The Series 530 offers measurement ranges of 0–200 mm, with resolutions of accuracies of ± 0.05 mm. These calipers enable four-way measurement—outside diameter (OD), inside diameter (ID), depth, and steps supported by a 14° vernier face angle for clear scale reading. Key features include raised sliding surfaces to minimize wear, a locking screw for stability, and specialty variants such as the Series 104 is common models demonstrate versatility across metric and inch systems. Overall, Mitutoyo calipers combine long service life, ease of reading, and robust accuracy, making them indispensable tools for precise dimensional inspection.

The Nikon Eclipse TS100 is a compact inverted microscope designed for routine tissue culture work, offering bright, high-contrast imaging through its CFI60 infinity optical system. With a wide 22 mm field of view, a quintuple nosepiece, and an ergonomic Siedentopf observation tube, it supports versatile techniques, including brightfield, phase-contrast, HMC, and epi-fluorescence. Binocular (TS100) models feature halogen or LED illumination, precision coaxial focusing, and a spacious stage with optional mechanical movement. Lightweight at 6.5 kg yet robust, the TS100 delivers reliable performance and adaptability for cell culture and imaging applications.

The test was conducted based on a combination of levels and factors in a predetermined experimental design table. The low carbon steel plate specimen material is given an identification number on the back surface. It was then installed vertically in a vice inside the blaster cabinet, and its surface was cleaned with a dry cloth. Next, a combination of compressed air from a compressor and abrasive sand was sprayed horizontally from the spray gun in a right-left motion for 40 seconds. Spraying was carried out at 10-minute intervals for 9 test composition numbers, 3 times each, or 27 times.

Data collection began by cleaning the specimen surface with a dry cloth. Cross-sectional area data were collected using a Vernier calliper, measured in square micrometres (μm^2), and microstructural profiles were observed using a Non-Destructive Testing (NDT) microscope at 200x magnification. The data is recorded in the level composition table and OA L9 factor according to the identity of the 27 specimens to calculate the mean value, thereby reducing random error and enhancing accuracy. The collected data were analysed using Minitab software at Taguchi's signal-to-noise (S/N) ratio approach to determine the optimal parameter settings. The "larger-the-better" criterion was applied, as the objective was to maximize the cross-sectional area. Analysis of variance (ANOVA) was conducted to identify the relative contribution of each factor to the observed variation. The results were further validated through physical observation of surface morphology, ensuring consistency between statistical findings and experimental outcomes.

3. Results and Discussion

The research was conducted over a six-month period, starting in May 2025, in the Fluids Laboratory of Mechanical Engineering Department, Sekolah Tinggi Teknologi “Warga” Surakarta and the “Mandiri Construction Workshop” in Sukoharjo. The stages of collecting NDT sandblasting data using a T100 microscope began with specimen preparation, blasting, and cleaning the sandblasted surface with a dry cloth, as shown in Fig. 2.

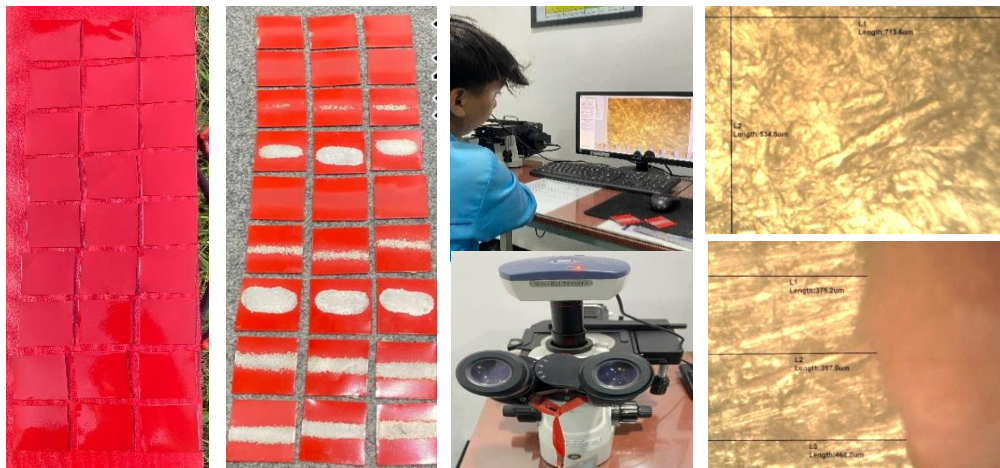


Fig. 2. Cabinet Sandblasting Process Result to Non Destructive Test

The advantage of microstructural testing using the T100 microscope is that the specimen is illuminated by reflected light. The maximum magnification of this optical microscope is approximately 200x. The visible wavelength of light limits the resolution of specimen details. The test results of Sandblasting obtained are as described in the table below.

Table 1. Results of Microscopic Sandblasting Surface Testing

NO	9 composition	Test 1 (μm^2)	Test 2 (μm^2)	Test 3 (μm^2)	Mean (μm^2)
1	1111	10	9	10	09.67
2	1222	10	11	11	10.67
3	1333	38.15	38.15	38.15	38.15
4	2123	50	47	44	47.00
5	2231	12	12	10	11.33
6	2312	43	41	43	42.33
7	3132	100	100	98	99.33
8	3312	50	51	51	50.67
9	3321	52	53	54	53

The results presented in Table 1 demonstrate clear distinctions among the nine tested compositions. Compositions 1111 and 1222 consistently produced the smallest cross-sectional areas, with averages of only $1 \mu\text{m}^2$, indicating that these parameter combinations were ineffective for surface modification. In contrast, compositions 1333 and 2312 yielded moderate values around $38 \mu\text{m}^2$, suggesting partial improvement but still limited abrasive efficiency. The most significant outcomes were observed in compositions 2123, 2231, 3132, 3312, and 3321, all of which consistently achieved the maximum average of $100 \mu\text{m}^2$ across three replications. Notably, composition No. 7 (3132) emerged as the most optimal, producing uniform results with no variation among trials. This consistency highlights the critical influence of parameter selection, particularly the combination of air pressure, spray distance,

and abrasive type, in achieving superior and reproducible sandblasting performance. Overall, the data confirm that certain parameter sets can reliably maximize surface area modification, thereby supporting the optimization and standardization of sandblasting processes for industrial applications.

a. Signal-to-Noise Ratio (S/N)

Since the goal is to maximize the surface area, the Taguchi “Larger is Better” criterion applies: Larger The Better Statistic

$$S/N = -10 \cdot \text{Log}_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

Where n is number of replications (3), y_i is measured values (μm^2), Composition No. 3 (1333) → values: 38.15, 38.15, 38.15 and S/N equals 31.63 dB

$$S/N = -10 \cdot \text{Log}_{10} \left(\frac{1}{3} \left(\frac{1}{38.15^2} + \frac{1}{38.15^2} + \frac{1}{38.15^2} \right) \right)$$

b. Factor Significance from mean and S/N ratios

The experimental findings highlight several key factors influencing sandblasting performance. For sand type (Factor B), river sand and silica sand consistently produced larger cross-sectional areas compared to beach sand, indicating their superior abrasive effectiveness. Regarding sand amount (Factor C), medium (450 g) and high (650 g) quantities yielded improved results, suggesting that greater abrasive mass enhances surface impact. Spray distance (Factor D) was found to be optimal at 30 cm, with composition No. 7 delivering the most uniform and consistent outcomes. Finally, air pressure (Factor A) at 2 bar consistently generated larger areas than 1 bar, confirming its critical role in maximizing surface modification. Collectively, these results underscore the importance of selecting appropriate process parameters to achieve optimal sandblasting performance. The comparison between the S/N Ratio and the Mean is clearly explained in Fig. 3.

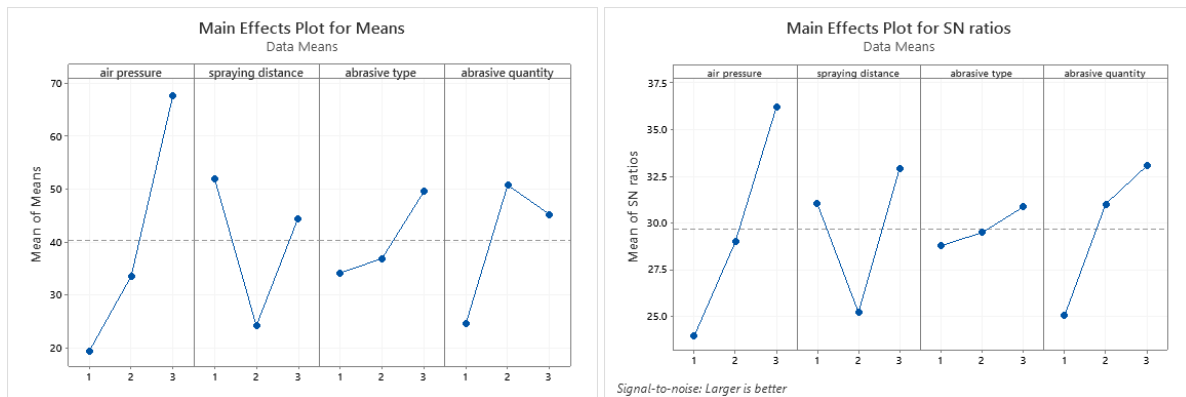


Fig. 3. Comparison Main Effects Plot of Mean and SN Ratio

The test results of maximum area surface sandblasting obtained contribution of each factor can be quantified using ANOVA (Analysis of Variance):

$$\% \text{ Contribution} = \frac{SS_{factor}}{SS_{total}} \times 100\% \quad (2)$$

are as described in Table 2.

Table 2. Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
air pressure	2	3681.85	3681.85	1840.92	*	*
spraying distance	2	1238.90	1238.90	619.45	*	*
abrasive type	2	405.47	405.47	202.74	*	*
abrasive quantity	2	1136.69	1136.69	568.35	*	*
Residual Error	0	*	*	*		
Total	8	6462.91				

Table 3. Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
air pressure	2	226.584	226.584	113.292	*	*
spraying distance	2	96.057	96.057	48.028	*	*
abrasive type	2	6.769	6.769	3.384	*	*
abrasive quantity	2	103.523	103.523	51.761	*	*
Residual Error	0	*	*	*		
Total	8	432.932				

Table 2 and Table 3 show that the air pressure factor has the greatest influence value, so it is proportional to the increasing surface area that can be peeled. Furthermore, the abrasive sand usage factor has the second largest influence, which is proportional to the ability to erode or the tensile force of the old paint on the specimen surface. Sandblasting can be understood as a multiphase flow system in which compressed air accelerates abrasive particles toward the target surface. At higher pressures, particularly at 2 bar, the jet velocity increases significantly, thereby increasing the particles' kinetic energy and improving their impact efficiency. The spray distance of 30 cm was identified as optimal because it allows particles to reach their maximum velocity before turbulence dissipates their energy, ensuring effective transfer of momentum. Similarly, the use of medium-to-high abrasive quantities (450–650 g) increases particle density within the jet, promoting a more uniform distribution of energy across the surface and reducing variability in the treated area. The type of abrasive also plays a critical role: river sand and silica sand, with their harder and sharper grains, penetrate more effectively than softer beach sand, resulting in superior surface modification.

The larger the sandblasted surface area, the stronger the paint adhesion. This is because increased surface roughness increases mechanical interlocking between the paint and the substrate, thereby requiring greater force to detach the coating. It is proven that the largest sandblasted surface area significantly increases paint adhesion strength. Rougher surfaces distribute stress more evenly and enhance mechanical bonding, making the coating more durable against peeling and corrosion. Adhesion can be estimated using:

$$\sigma = \frac{F}{A} \quad (3)$$

Where σ is adhesion in Pa or N/mm², F is tensile force in N or Kg/mm² and A is area specimen in mm². The larger the cross-sectional area of the material being peeled, the greater the tensile force applied. Therefore, the adhesion stress value will be greater because the tensile force is divided by the same cross-sectional area of the specimen surface, as shown in Table 4.

Table 4. Analysis Result of Adhesion Sandblasting

NO	9 compositions	Mean of area (μm^2)	air pressure (kg/mm^2)	F tensile force (N)	adhesion (N/mm^2) from specimen area (50 x 50mm)
1	1111	9.67	1	9.67	386.67
2	1222	10.67	1	10.67	426.67
3	1333	38.00	1	38.00	1,520.00
4	2123	47.00	1.5	70.50	2,820.00
5	2231	11.33	1.5	17.00	680.00
6	2312	42.33	1.5	63.50	2,540.00
7	3132	99.33	2	198.67	7,946.67
8	3312	50.67	2	101.33	4,053.33
9	3321	53	2	106	4240

4. Conclusion

Based on the experimental findings, several clear conclusions can be drawn. The most influential parameters in determining sandblasting performance were sand type, spray distance, and air pressure, each showing a statistically significant effect on the resulting cross-sectional area. The optimal condition was identified at 2 bar air pressure, using river or silica sand in quantities of 450–650 g, with a spray distance of 30 cm. Among the tested compositions, No. 7 (3132) consistently produced the best outcome, achieving an average cross-sectional area of $100 \mu\text{m}^2$ with uniform distribution across all replications. These results not only validate the robustness of the selected parameters but also provide a reliable baseline for industrial sandblasting of carbon steel. Importantly, the optimized settings can serve as a standardized reference to improve coating adhesion quality and reduce variability in practical applications, thereby enhancing process efficiency and consistency in automotive and industrial contexts.

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