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Research Article

Design and Performance Evaluation of a Motor-Driven Adjustable Speed Tool for Corrosion Removal on Bolt Threads in Steam Power Plant Applications

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ABTRACT

This study develops and experimentally evaluates a portable motor-driven adjustable-speed tool for on-site removal of corrosion from bolt threads during steam power plant maintenance. The research objectives are to design and fabricate the proposed tool and to quantify the effects of motor speed and bolt size on cleaning performance and operating constraints. A prototype integrating a variable-speed electric motor (450-1800 rpm), a rotating wire brush, and a controlled clamping mechanism was fabricated and tested on twelve naturally corroded bolts (four per size): M14×60 mm, M16×60 mm, and M20×80 mm, at 450, 900, 1350, and 1800 rpm. Cleaning time, vibration (mm/s), and surface temperature (°C) were measured, and a time-based cleaning-efficiency index was calculated; the effects of speed and bolt size were evaluated using a two-factor general linear model with Tukey post-hoc comparisons ($\alpha=0.05$). Increasing motor speed reduced cleaning time from 1.23 to 0.39 min for M14, 1.37 to 0.36 min for M16, and 2.20 to 1.34 min for M20, while vibration increased from ~0.4-0.5 mm/s to 2.6-3.4 mm/s and temperature increased to 35.8-38.2 °C. Cleaning efficiency reached 68.3% (M14) and 73.7% (M16) at 1800 rpm but only 39.1% for M20, indicating reduced effectiveness on larger thread dimensions. An operating window of 1350-1800 rpm provides a practical trade-off between cleaning speed and operational stability.

1. INTRODUCTION

PT ABC is a company specializing in the processing of metal materials, with various products including chrome alloy. Steam power plants operate under demanding service conditions, including high temperatures, pressure fluctuations, and chemically aggressive environments, which challenge the reliability of mechanical components. In such systems, bolts are essential fastening elements widely used in pumps, valves, heat exchangers, turbines, and auxiliary equipment due to their ability to provide strong yet detachable joints (Lacey et al., 2019; Lai et al., 2021; Yang et al., 2023). Consequently, bolt integrity plays a critical role in maintaining operational safety and minimizing unplanned shutdowns.

In steam power plant operations, bolts are repeatedly subjected to thermal cycling during start-up and shutdown, exposure to condensate from steam leakage, and prolonged high-humidity conditions during maintenance outages. These operational phenomena accelerate corrosion development, particularly on threaded regions where crevice effects intensify electrochemical reactions (Li et al., 2020). Field observations at the steam power plant operated by PT ABC indicate that bolt thread corrosion is a recurring maintenance problem, frequently causing thread seizure, increased disassembly torque, and a risk of bolt fracture. As corrosion products accumulate, mechanical strength and dimensional accuracy deteriorate, ultimately extending maintenance duration and increasing plant downtime (Ahmed et al., 2021; Harsimran et al., 2021).

In practice, corroded bolt threads are commonly cleaned using handheld wire brushes or angle grinders because of their simplicity and availability. However, such conventional methods suffer from notable limitations.

Cleaning effectiveness depends heavily on operator skill, brushing angle, and applied force, leading to inconsistent results. Moreover, uncontrolled abrasive action may cause excessive material removal and degradation of the thread profile, reducing bolt reusability and accelerating subsequent corrosion processes (Wei et al., 2025). These limitations become increasingly critical during large-scale maintenance outages where numerous bolts must be serviced within restricted timeframes.

Various corrosion mitigation and removal techniques have been reported in the literature. Preventive approaches, including protective coatings, corrosion inhibitors, and cathodic protection, are effective in slowing corrosion rates but are often impractical for small and numerous fasteners during in-situ maintenance operations (Olajire, 2018; Sharun et al., 2022; Haris et al., 2021; Kaur et al., 2022) Alternative corrosion removal methods, such as sandblasting, ultrasonic cleaning, and chemical treatments, have demonstrated effective cleaning performance under controlled conditions; however, these techniques typically require specialized facilities, immersion processes, or involve environmental and occupational safety concerns (Belardi et al., 2019; D’Antimo et al., 2020).

Recent studies have explored motor-driven mechanical cleaning tools that offer improved control over operational parameters such as rotational speed and contact conditions (Malashonak, 2025). Nevertheless, the reviewed literature indicates that portable, adjustable-speed tools specifically designed for bolt thread corrosion removal during on-site steam power plant maintenance remain limited. Furthermore, quantitative investigations that simultaneously evaluate cleaning efficiency, vibration behavior, and thermal effects across different bolt sizes are still insufficient. This lack of systematic evaluation represents a clear research gap addressed in the present study.

Based on the identified challenges and research gaps, this study aims to design and experimentally evaluate a portable motor-driven adjustable-speed tool for localized corrosion removal on bolt threads in steam power plant applications. The proposed tool integrates a variable-speed electric motor, a rotating wire brush, and a controlled clamping mechanism to ensure stable contact conditions and repeatable cleaning performance while minimizing thread damage. Experimental evaluations focus on the effects of motor speed on cleaning time, vibration level, and surface temperature. Tests were conducted on M14 × 60 mm and M16 × 60 mm bolts representing common maintenance applications, as well as M20 × 80 mm bolts to examine tool performance limits for larger thread sizes.

The contribution of this study lies in providing a practical, operator-friendly solution for bolt thread restoration in steam power plant maintenance, supported by systematic experimental evaluation. The results provide quantitative insights into the relationships among motor speed, cleaning efficiency, and operational constraints, thereby supporting informed selection of operating parameters that balance effectiveness, safety, and tool stability. By improving the efficiency and consistency of corrosion removal, the proposed tool has the potential to reduce maintenance time, extend bolt service life, and enhance the overall reliability of steam power plant operations.

2. METHOD

This study was carried out in the turbine mechanic division of PT ABC PLTU by employing experimental methods, systematic observation, and direct documentation. The primary objective was to develop a specialized bolt thread cleaning tool, with cleaning duration and motor rotational speed selected as key parameters for data collection and performance evaluation. Sample preparation in this study was designed to reflect actual corrosion conditions encountered during steam power plant operation. Corroded bolt specimens were obtained directly from routine maintenance activities, during which visual inspections identified numerous bolts exhibiting corrosion in the threaded regions. The corrosion states were selected based on visual assessment, and only bolts showing relatively uniform surface corrosion without severe localized damage, thread deformation, or cracking were included to ensure comparable initial conditions across samples. A total of 12 bolt specimens were tested, comprising four bolts of each size (M14 × 60 mm, M16 × 60 mm, and M20 × 80 mm), selected for their frequent use in field applications and for their availability during maintenance activities. The corrosion on the bolts developed naturally as a result of operational and environmental factors associated with steam power plant operation, including exposure to high temperatures, steam, condensate, humidity, and repeated thermal cycling during start-up and shutdown. Such conditions are widely recognized as primary contributors to corrosion initiation and propagation on steel fasteners used in steam power plant systems (Ahmed et al., 2021). The stages of the research methodology are illustrated in Fig. 1, which comprises tool design, prototype development, experimental testing, data collection, and data analysis.

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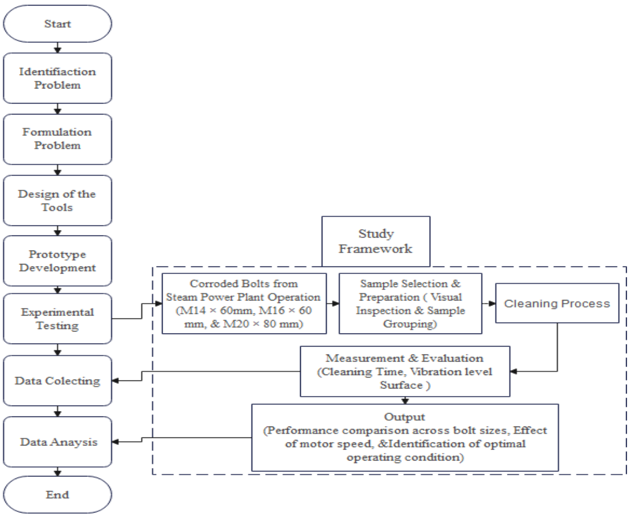

Fig .1. Research Methodology

1. *Design of the Tools*

The design of the rust-cleaning tool for bolt threads was developed using Computer-Aided Design (CAD) applications, resulting in a model that comprehensively represents its functions, components, and operational mechanisms. The design was carried out with functional, safety, and ergonomic considerations to ensure the tool's effectiveness in an industrial work environment. The final design is shown in Fig 2.

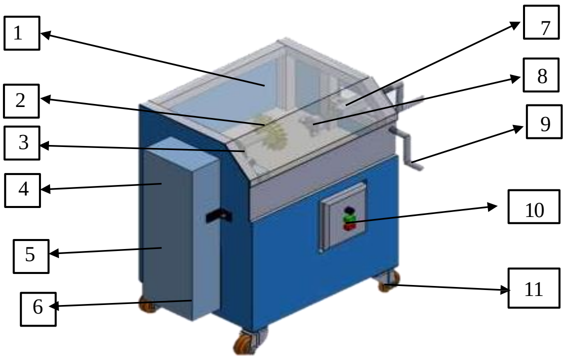

Fig .2. Design Tools

The main structure of the tool is equipped with an acrylic cover (1) that serves as a protective enclosure during the cleaning process. This cover enables operators to directly observe the cleaning process without physical contact with moving components, thereby enhancing safety. The rust removal process itself is performed by a round wire brush (2) rotating at a certain speed to scrape off corrosion layers from the bolt threads. The brush rotation is driven by a transmission system consisting of a pulley (4) and V-belt (5), supported by a pillow block (3) that stabilizes the shaft and minimizes friction. This configuration ensures efficient and durable transmission performance. The entire transmission mechanism is protected by a transmission system cover (6), preventing operators from accidental contact with fast-rotating components. On the workpiece side, the bolt is clamped by a 3-jaw chuck (8) mounted on a cross slide (7). This mechanism ensures precise positioning of the bolt so that its threads come into uniform contact with the rotating brush. The turning lever (9) allows operators to control the forward and backward movement of the workpiece, adjusting the cleaning distance and pressure according to the degree of corrosion. An essential feature of the tool is motor speed control, managed by a Variable Frequency Drive (VFD) pad controller (10). This system enables operators to regulate the brush's rotational speed depending on the severity of rust, thereby optimizing cleaning results. Furthermore, the tool is equipped with caster wheels (11), providing high mobility and enabling easy relocation within the workplace. By integrating these components, the tool design combines cleaning efficiency, operator safety, transmission reliability, and mobility. This makes the tool not only technically feasible but also practical for industrial maintenance operations.

2. *Prototype Development*

At this stage, the tool's design is complete, resulting in a prototype as illustrated in Fig. 3, in which all main and supporting components are assembled on the frame. The frame is constructed from hollow steel for its high durability and widespread availability. The hollow steel used in this study has dimensions of 32 × 32 mm, a thickness of 2 mm, and a total length of 2 × 600 cm. In addition to the hollow steel, a steel plate measuring 52 × 40 cm with a thickness of 2 mm was also utilized. Prior to the testing phase, all components were thoroughly inspected to ensure that each part was properly and safely installed

Fig .3. Prototype Tools

3. *Experimnetal Testing*

Experimental testing was conducted to evaluate the performance of the proposed adjustable-speed cleaning tool on corroded bolt threads with different dimensions. The specimens consisted of three bolt sizes commonly used in steam power plant maintenance, namely M14 × 60 mm, M16 × 60 mm, and M20 × 80 mm, which were selected to assess tool performance across varying thread

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sizes and lengths, as differences in fastener dimensions are known to influence corrosion behavior and cleaning effectiveness (Mokhtari et al., 2024). The cleaning process was performed using a rotating wire brush driven by an electric motor equipped with variable-speed control, adjustable over 450–1800 rpm to accommodate variations in bolt size and corrosion severity, consistent with previous studies on mechanical corrosion removal (Lachowicz & Lachowicz, 2021). To minimize operator-related variability, all experiments were carried out by a single trained operator following a standardized cleaning procedure, with consistent tool positioning, contact pressure, and alignment between the brush and the bolt axis, as recommended in controlled mechanical cleaning experiments (Wei et al., 2025). The end of cleaning was defined using objective criteria, namely the complete removal of visible corrosion products and the achievement of a uniform metallic appearance along the entire threaded length, which has been widely adopted as a practical endpoint in surface cleaning studies (Ta & Kim, 2020). Cleaning time was recorded from the initial contact between the brush and the bolt until the defined end-of-cleaning condition was reached. During the cleaning process, motor speed was verified using a tachometer, vibration levels were measured using a vibration meter mounted on the pillow block and electric motor housing (mm/s), and surface temperature rise was monitored using a thermometer. Temperature measurements were taken immediately after cleaning at three locations along the threaded region, and the average value was used for analysis, following common practices for evaluating friction-induced thermal effects during mechanical surface treatment (Olajire, 2018; Sharun et al., 2022). All measurements were conducted under similar ambient conditions to ensure data consistency and repeatability. The bolt specimens and their corresponding dimensions are summarized in Table 1.

Table 1. Bold Samples Used in The Study

Dimension Bolt	Sample
M14 × 60 mm	
M16 × 60 mm	
M20 × 80 mm	

4. *Collecting Data*

The data collection process in this research was conducted through experimental testing of a motor-driven adjustable speed cleaning tool applied to corroded bolt threads. Four main parameters were measured during the experiments, namely cleaning time, motor speed, temperature, and vibration. Cleaning time was recorded using a digital stopwatch, motor speed was measured with a tachometer, while temperature and vibration were monitored using appropriate sensors installed near the operating tool. These parameters were chosen to represent both the tool's performance and operational characteristics. Cleaning time directly reflects the effectiveness of corrosion removal; motor speed is the main variable that can be adjusted, whereas temperature and vibration provide important insights into the thermal and mechanical stability of the cleaning process. Table 2 presents the experimental test results, showing the recorded data for each parameter according to the applied operating conditions of the cleaning tool.

Table 2. Experimental Test Results

Sample Dimension	Motor Speed (rpm)	Cleaning Time (min)	Vibration (mm/s)	Temperature (°C)
M14×60mm	450	1.23	0.5	33.1
	900	1.12	1.1	33.9
	1350	0.49	1.9	35.4
	1800	0.39	2.6	35.8
M16×60mm	450	1.37	0.5	32.9
	900	1.18	1.1	35.7
	1350	0.54	2.0	37.0
	1800	0.36	3.3	38.0

Sample Dimension	Motor Speed (rpm)	Cleaning Time (min)	Vibration (mm/s)	Temperature (°C)
M20×80mm	450	2.20	0.4	32.4
	900	2.18	1.2	34.5
	1350	1.47	2.3	36.7
	1800	1.34	3.4	38.2

*(single measurements per bolt size × motor speed; n = 1 per condition)

The proposed model integrates the key influencing parameters of cleaning time, vibration, and temperature into a unified performance assessment. Cleaning efficiency (η) was quantified using a time-based metric (Eq. 1): η = (t_max − t)/t_max × 100%, where t_max is the longest cleaning time for the corresponding bolt size and t is the measured cleaning time at a given motor speed. Vibration and surface temperature were recorded concurrently and treated as operational constraints; therefore, optimal operating points maximize η while keeping vibration and temperature within acceptable limits. This combined approach enables direct comparison of cleaning effectiveness across motor speeds and bolt sizes. Statistical Analysis

$$\eta = \frac{t_{max}}{t_{max} - t}\, x\, 100\% \qquad (1)$$

Statistical analysis was performed using a two-factor general linear model (GLM) with motor speed (450, 900, 1350, and 1800 rpm) and bolt size (M14 × 60 mm, M16 × 60 mm, and M20 × 80 mm) as fixed factors (Montgomery, 2019). Because each bolt size × speed condition was represented by a single specimen (n = 1 per cell; total n = 12), the full categorical interaction C(speed) × C(size) could not be estimated; therefore, the categorical GLM tests only main effects. To explore potential interaction trends, an additional model treated motor speed as a continuous predictor (centered and scaled per 1000 rpm) and included the motor speed × bolt size interaction. Significance was accepted at α = 0.05, effect size is reported as partial eta squared (ηp^2) (Wang et al., 2023), and post-hoc comparisons among motor speed levels used Tukey's HSD on least-squares means with the pooled model MSE (Wei et al., 2025). For Figures 4–7, error bars represent 95% confidence intervals of the model-estimated means.

3. RESULT AND DISCUSSION

Tool Performa Evaluation

The performance of the motor-driven adjustable-speed cleaning tool was evaluated through a series of experimental tests using three bolt sizes typically found in steam power plant applications: M14 × 60 mm, M16 × 60 mm, and M20 × 80 mm. Each bolt was cleaned at four motor speeds: 450 rpm, 900 rpm, 1350 rpm, and 1800 rpm. The key performance parameters measured during the tests included cleaning time (minutes), vibration level (mm/s), surface temperature (°C), and visual cleanliness (based on physical inspection of bolt samples). As shown in Fig. 4, cleaning time decreased consistently with increasing motor speed for all bolt sizes. For example, in the case of the M16 × 60 mm bolt, cleaning time reduced from 1.37 minutes at 450 rpm to 0.36 minutes at 1800 rpm. This trend is consistent with brushing theory: increasing brush rotation speed increases the number of bristle impacts per unit area and time, thereby increasing abrasion/removal of surface layers (Avianto et al., 2020; Iskandar & Ksatria Arya Pandega Prasetyandi, 2023). Rotary bristle-based surface preparation has also been reported for corrosion removal applications, supporting the use of this class of tools for maintenance tasks (Li et al., 2020). Two-factor GLM analysis confirmed that motor speed and bolt size significantly affected cleaning time (motor speed: F(3,6) = 290.43, $p < 0.001$, $\eta p^2 = 0.993$; bolt size: F(2,6) = 574.44, $p < 0.001$, $\eta p^2 = 0.995$). Tukey HSD on least-squares means indicated that 1350 and 1800 rpm yielded significantly shorter cleaning times than 450 and 900 rpm ($p < 0.001$), while 450 and 900 rpm were not significantly different ($p = 0.108$).

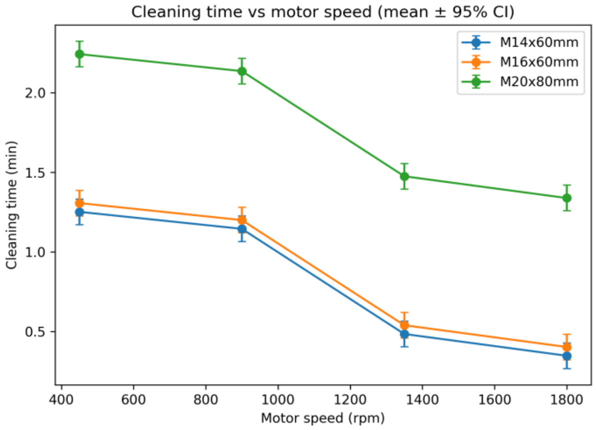

Fig .4. Cleaning time vs. motor speed for M14, M16, and M20 bolts (error bars: 95% CI of GLM-estimated means).

Surface temperature of the bolts after cleaning increased with higher rpm, peaking at 38.2°C for the M20 bolt at 1800 rpm (Fig. 5). This rise is consistent with frictional heat generation in dry sliding/abrasive contacts, where increased relative motion can increase heat input at the contact interface (Kennedy., 2013). Similar brushing studies have also reported that increasing brushing intensity (e.g., higher rotation speed and/or longer contact) can increase temperature and surface-modification effects (KM et al., 2024). Motor speed had a significant effect on surface temperature (F(3,6) = 22.61, $p = 0.001$, $\eta p^2 = 0.919$). Pairwise comparisons showed that 1800 rpm produced significantly higher temperatures than 900 rpm ($p = 0.017$) and 450 rpm ($p = 0.001$), whereas the difference between 1350 and 1800 rpm was not significant

($p = 0.430$). A continuous-speed interaction model suggested that the temperature increase per 1000 rpm was larger for bigger bolts (M14: +2.13 °C; M16: +3.69 °C; M20: +4.36 °C; interaction $p = 0.031$).

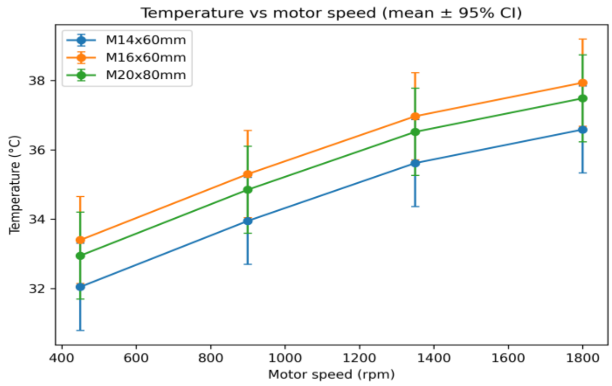

Fig .5. Surface temperature vs. motor speed for M14, M16, and M20 bolts (error bars: 95% CI of GLM-estimated

The vibration level of the tool increased with motor speed (Fig. 6). While low at 450 rpm (~0.5 mm/s), vibration rose to over 3 mm/s at 1800 rpm, particularly for the larger M20 bolt. This behavior is expected in rotating systems because higher rotational speed can amplify dynamic excitation (e.g., due to rotating unbalance and structural resonances) and thus increase measured vibration response (Harsimran et al., 2021). Therefore, vibration must be considered alongside cleaning time when selecting an operating point. Vibration increased significantly with motor speed ($F(3,6) = 80.52$, $p < 0.001$, $\eta_p^2 = 0.976$), and all pairwise speed comparisons were significant (Tukey $p \leq 0.038$). Bolt size did not have a significant main effect on vibration in the two-factor model ($p = 0.228$).

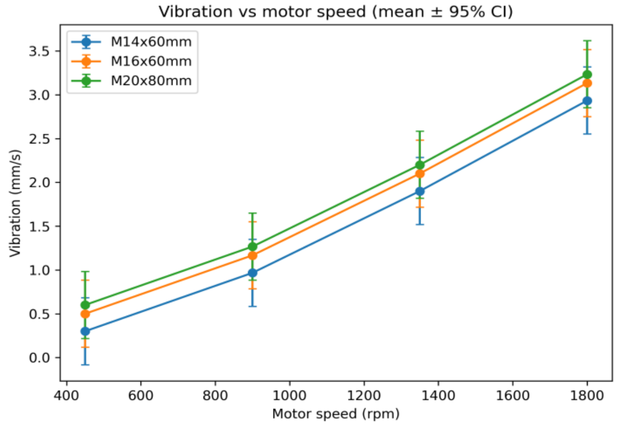

Fig .6. Vibration vs. motor speed for M14, M16, and M20 bolts (error bars: 95% CI of GLM-estimated means).

Visual inspection of bolt threads before and after cleaning (Table 3) indicates that the proposed motor-driven variable-speed tool effectively removes corrosion from threaded fasteners. Post-cleaning images show more uniform, exposed thread profiles and reduced oxide layers, with no observable thread deformation, suggesting that the brush action is sufficiently aggressive to remove corrosion while preserving thread geometry.

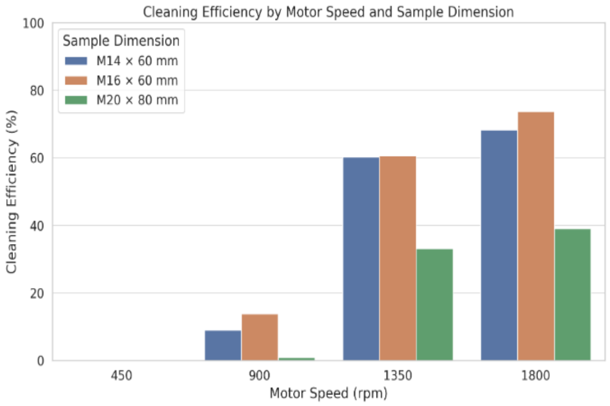

Fig .7. Cleaning Efficiency by Motor Speed and Sample Dimension

Table 3. Demonstration Results: Prototype Motor-Driven Adjustable-Speed Bolt Cleaning Tool

Dimension Bolt	Sample
M14 × 60 mm	
M16 × 60 mm	
M20 × 80 mm	

Cleaning Efficiency Across Motor Speeds

Fig. 7 summarizes cleaning efficiency across motor speeds for each bolt size, where efficiency was derived from the time-based metric in Eq. 1. As motor speed increased from 450 rpm to 1800 rpm, cleaning efficiency improved for all sample dimensions. The M16 × 60 mm bolts achieved the highest average efficiency (up to 73.72%), suggesting a favorable interaction between brush contact and thread geometry at higher speeds. In contrast, the M20 × 80 mm bolts demonstrated lower efficiency (~39.09%), consistent with the larger threaded surface area requiring more brushing work for equivalent cleanliness (Neubauer et al., 2010). Cleaning efficiency, derived from cleaning time, was significantly influenced by motor speed ($F(3,6) = 36.82$, $p < 0.001$, $\eta p^2 = 0.948$). Tukey HSD showed that efficiencies at 1350 and 1800 rpm were significantly higher than at 450 and 900 rpm ($p \leq 0.0035$), while the difference between 1350 and 1800 rpm was not significant ($p = 0.601$).

Fig .7. Cleaning Efisiensi for M14, M16, and M20 bolts

The results show a positive correlation between motor speed and cleaning efficiency. As rotational speed increases, the time required for cleaning decreases, leading to a higher efficiency score. At 1350 rpm, both M14 and M16 bolts reached an efficiency of approximately 60%, while M20 bolts remained around 33%. At the highest tested speed (1800 rpm), efficiency for M16 × 60 mm peaked at nearly 75%, followed closely by M14, while M20 bolts reached approximately 40%. This discrepancy is attributed to the larger surface area and thread volume of the M20 bolt, which inherently requires more brushing work even at higher speeds (Tang et al., 2024). Similar improvements in mechanical cleaning/grinding efficiency with increasing rotational speed have been reported in related material removal processes. However, the efficiency trend begins to plateau at higher rpm, especially for smaller bolts, indicating diminishing returns beyond 1350 rpm in some cases. Such diminishing returns are consistent with brushing process observations where the effective bristle engagement/contact conditions depend on process parameters and can limit further surface modification gains (Teichers et al., 2018). Therefore, when balancing efficiency with operational stability, 1350 rpm may offer a favorable compromise between cleaning performance and vibration/temperature increases (Teichers et al., 2018; Kennedy, 2013).

Overall, increasing motor speed improves cleaning efficiency but also increases vibration and surface temperature (Figures 3–5). This trade-off is typical for rotary abrasive/brushing tools, where higher speed increases both material removal action and dynamic/thermal loads increases (Teichers et al., 2018; Kennedy, 2013). Accordingly, the recommended operating range for the tested configuration is 1350–1800 rpm, with the final selection depending on the acceptable vibration level and thermal rise for the intended maintenance task.

4. CONCLUSION

The objectives set out in the Introduction, namely to design a portable motor-driven adjustable-speed cleaning tool and to demonstrate its effectiveness for localized corrosion removal on bolt threads used in steam power plant maintenance, are supported by the experimental results presented in the Results and Discussion. The prototype achieved substantial reductions in cleaning time and a clear improvement in time-based cleaning efficiency for M14 × 60 mm and M16 × 60 mm bolts at higher speeds while maintaining thread integrity. In contrast, performance was lower for M20 × 80 mm bolts: cleaning time remained longer (2.20 min at 450 rpm to 1.34 min at 1800 rpm) and the time-based efficiency reached only ~39% at 1800 rpm, indicating that the current brush–clamp configuration is less effective for larger thread dimensions and defines a key limitation of the present prototype.

Key findings indicate that increasing motor speed accelerates corrosion removal but also raises vibration and surface temperature, implying an operational trade-off. An operating window of 1350 to 1800 rpm provides a practical balance between removal effectiveness and acceptable mechanical and thermal loads for the tested configuration, particularly for M14 and M16 bolts. For larger bolts (M20), increasing speed alone produced diminishing returns in efficiency while further increasing vibration, suggesting that future performance gains will depend more on design optimization than on speed escalation.

For future development and application, the prototype can be advanced through (i) quantitative validation of surface cleanliness using image-based area analysis and gravimetric weight-loss measurements, (ii) incorporation of vibration damping and active cooling to extend continuous operation at higher speeds, and (iii) integration of sensor feedback and automated pressure control for repeatable field deployment. To address the lower performance observed on M20 bolts, future work should prioritize design optimization for larger threads, such as brush geometry/stiffness scaling, improved access to deeper thread valleys, higher available torque, and adaptive clamping/contact-pressure control. Field trials in actual plant outage conditions and long-term durability testing of the brush and drive components are recommended to support industrial adoption and to refine operational guidelines for maintenance crews.

Author Contribution: Kadex Widhy Wirakusuma conceived and supervised the study and led the manuscript preparation. Yudi Siswanto, Agus Salim Opu, and Angga Tegar Setiawan led the experimental design and prototype development. Ereik Aristya Pradana Putra and Muhammad Alfian performed the experimental testing, data collection and data analysis. Abdul Malik Alfafa contributed to prototype fabrication, instrumentation setup, and assisted in data interpretation. All authors contributed to drafting and critically revising the manuscript, and all authors read and approved the final manuscript

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NOMENCLATUR

The meaning of symbols used in equations and other symbols presented in your article should be provided in this section.

η = Efficiency Of The Cleaning Process
t_{max} = Maximum Cleaning Time For The Corresponding Bolt Size
t = Measured Cleaning Time At A Given Speed

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