The influences of corrosion on the tightening and anti-loosening properties of a flank-locking precision locknut

 Huey-Ling Chang 1, Chih-Ming Chen 2,∗ and Chun-Ying Lee 3

1Department of Chemical and Materials Engineering, National Chin-Yi University of Technology, Taichung, Taiwan
2Department of Mechanical Engineering, National Chin-Yi University of Technology, Taichung, Taiwan
3Graduate Institute of Manufacturing Technology, National Taipei University of Technology, Taipei, Taiwan

∗ Corresponding author: cmchentc@gmail.com

ABSTRACT

Locknut is a critical component used in the precision machinery and its stable service performance over a long period of time in a variety of different environments presents a crucial challenge. In this study, a flank-locking precision locknut was pretreated in an immersion corrosion of 5 wt% NaCl solution to simulate the possible corrosion effects. The tightening and loosening of the locknut after 0-, 1-, 2- and 4-h corrosion treatments, respectively, was tested according to the ISO 2320 Standard. An in-house test setup with horizontal configuration was employed in measuring the torque–axial force characteristics under loading–unloading cycles. It was found that the corrosion of the locknut accelerated after 1-h immersion. The corroded specimens after 2- and 4-h treatment demonstrated more variance in measured tightening and loosening torques than their less corroded counterparts. However, after five loading–unloading cycles, the variance in measured torque decreased and the associated torque constants became more stable. Moreover, the torque constants were ~10% higher for the 2- and 4-h corrosion-treated locknuts than their pristine counterpart. The surface morphology after corrosion and friction wear was closely related to the measured testing results.

KEYWORDS: immersion corrosion, anti-loosening performance, flank-locking precision locknut, surface morphology

1. INTRODUCTION

The design and assembling techniques are critical in the manufacturing of precision machinery. The weather and environment in which the machinery is located also play important roles in maintaining their required performances. Severe challenge usually occurs for the machinery in hot and humid environment where corrosion of critical components is almost impossible to prevent. Among the critical components of precision machinery, assembling and maintaining the functions of precision locknut is crucial for the designed accuracy and service life of a machine tool. Although several studies, such as those by Dragoni [1], Kenny and Patterson [2] and Bhattacharya et al. [3], had reported the influences of stress states in the bolt and nut pair on their anti-loosening performance, very few studies have been devoted to the possible effects of corrosion. Nevertheless, it can be expected that corrosion could manifest its influences in many circumstances.

Sase et al. [4] and Sase and Fujii [5] reported that the loosening of threaded fastener had been caused mainly by the relative slippage of two mating surface pairs: threaded surfaces of bolt and nut, and contact surfaces of object and fastener. The repeated occurrences of the slippage denoted the relative rotation between bolt and nut. Only one of the slippages was impeded; the loosening of the fastener could be prohibited.

The control of resistance to slippage can be attained by tightening the fastener to the preset torque. Eccles et al. [6] revealed that the loosening of the threaded fastener usually deteriorated the thread surface and increased the friction coefficient. Subsequently, lower pretension developed if the same tightening torque was applied. They also reported that the friction coefficient at the thread surface was higher than that at the collar surface of nut. However, the friction coefficients at both thread surface and collar surface converged to a consistent value after five to six tightening–loosening cycles. The stabilized friction coefficient was also influenced by the level of pretension in the fastener.

The reliability of a fastener bolt/nut pair against fatigue failure is usually related to its stress state under service. Zhao [7] calculated the stress distribution in the mating nut of a fastener pair using the finite element method and found that non-uniform stress was distributed over the contact thread pair. Plastic deformation occurred at some critical regions and mostly near the root of the first contact thread pair. Their results were further applied to the design modification of the bolt/nut fastener pair and improved its performance.

In addition to the material failure in a fastener pair, the loss of designated clamping function in service is equally unacceptable. Friction usually is closely associated with the axial pretension as well as the anti-loosening of the fastener tightened with a set torque. The test results reported by Hubbertz and Friedrich [8] revealed the correlation of friction with respect to the material type, axial pretension, number of repeated tightening/loosening...
cycles and angular speed in turning. Baragetti et al. [9] also reported that the material type of the bolt mated with the nut made of beryllium–copper alloy and the use of lubricant determined the friction characteristics of the mating pair. Izumi et al. [10] studied the loosening of the fastener subjected to shear loading by using finite element analysis. They argued that as the microtorque accumulated on the contact surface of threads reached a threshold, local slip occurred and loosening of the fastener pair emerged.

In the corrosive environment such as in marine environment or on seabed, Esalkul and Martin [11] stressed the importance of using strong fastener with good corrosion resistance. Overloading, fatigue and corrosion-induced cracking of the fastener were its main failure modes [12]. Therefore, cathodic protection was found to be an effective measure to alienate the fastener failure associated with corrosion. Although cathodic protection was effective in reducing corrosion influence for fastener made of high-strength steel with lower hardness, environmentally assisted cracking occurred for the one of higher hardness steel due to hydrogen embrittlement [13]. Hydrogen-induced intergranular stress corrosion cracking for the fastener made of high-strength NiCrMo steel was also reported by Jha et al. [14].

Zelinka et al. [15] investigated the corrosion of metallic fastener embedded in wood and exposed to atmospheric environment. The model predicted the corrosion depth per year of the fastener in different American cities. They found most fastener’s corrosion was limited to 10 mm below the surface with maximum corrosion within 1–5 mm below the surface. The corrosion was found sensitive to the water content in the wood.

Majzoobi et al. [16] performed fatigue testing on five different sized ISO and Unified bolts with coarse and fine threads, respectively. The test was performed at a frequency of 2–5 Hz under sinusoidal cyclic loading. The results revealed the fatigue life of the bolt with coarse thread was always better than the fine one for both thread systems.

However, with the understanding of possible critical influence of corrosion on the performance of the fasteners, few studies on the effect of corrosion on the locknut, used in the precision machine tools, automation production facility or offshore windmills, have been reported. The failure of locknut can degrade the accuracy of machine tools or cause safety issue and high maintenance cost in the worst scenario. With the extensive applications of ball-screw drive systems in precision machinery of capital-intensive facility, the possible influence of corrosion on the performance of locknut needs attention. Therefore, the influence of corrosion on the tightening and anti-loosening performance of a flank-locking precision locknut was investigated experimentally in this study.

\section{Performance Parameters}

\subsection{Torque Constants}

Regarding the conventional relationship between the applied torque $T$ and the induced axial tension $F$ of a fastener bolt/nut pair, it takes different forms in tightening and loosening due to the change in the direction of friction force. Therefore, they usually can be written as follows in tightening and loosening, respectively [17,18]:

\begin{equation}
K = \frac{T_F}{F d_m},
\end{equation}

\begin{equation}
K' = \frac{T_L}{F d_m}.
\end{equation}

In the above equations, $T_F$ and $T_L$ denote the tightening torque and loosening torque, respectively, while $F$ is the axial tension and $d_m$ is the effective diameter of the thread. $K$ and $K'$ are the corresponding torque constants in tightening and loosening of the fastener pair, respectively. $d_m$ is the calculated mean diameter of the measured peak and root diameters of the thread profile. It should be understood that within linear range these torque constants remain unchanged but have different magnitudes in tightening and loosening, as mentioned previously.

When the torque measurement was performed for the locknut after different hours of immersion corrosion, different torque constants could be obtained. Therefore, the percentage of corrosion influence on the measured torque constant was calculated as follows:

\begin{equation}
\text{percentage of corrosion influence} = \frac{K_i - K_0}{K_0} \times 100%,
\end{equation}

where $K_i$ and $K_0$ are the torque constants after different hours of immersion corrosion, respectively.

\subsection{Coefficient of Variance}

Three specimens for each measurement were employed in this study in order to evaluate the variation of the results. Therefore, coefficient of variance (CV) was calculated accordingly:

\begin{equation}
CV = \frac{S}{X},
\end{equation}

where $S$ is the standard deviation and $X$ the mean values.
where $\bar{X}$ and $S$ are the mean and standard deviation for each set of measurements, respectively.

3. EXPERIMENTAL

3.1 Specimens

3.1.1 Flank-locking precision locknut

The locknut studied herein was a flank-locking precision locknut MF30, manufactured by Nikki Co., Taiwan, with the dimensional specifications presented in Fig. 1. The body of locknut was made of SCM 440 alloy with hardness HRC 28–32. Its M30 $\times$ 1.5 internal thread was machined with 4H surface finish defined by the ISO 965-3 Standard. On its outer circumference, there were three equally spaced M6 set screws, which were made of SCM 435 with hardness HRC 45–53 and manufactured according to the ISO 4026 Standard. At the tip of each set screw, there was a lining copper piece (brass C3604) to buffer the contact between set screw and bolt thread. It should be mentioned that these set screws are usually tightened after the locknut has been assembled with required axial tension in the bolt to ensure better anti-loosening resistance of the whole assembly. However, as mentioned previously, the main purpose of this study was simply to investigate the influence of corrosion on the tightening and loosening characteristics of the locknut. The set screws were not tightened throughout this study.

3.1.2 Standard bolt

Figure 2 presents the standard bolt dimensional specifications used in this study to assemble with the locknut specimens. It was designed to simulate the industrial application of locknut in
Influence of corrosion on tightening and anti-loosening properties of flank-locking precision locknut

3.1.3 Lubricant

In the assembling of locknut to its mating bolt, the application of lubricant usually provides the benefits of reducing friction and wear, improving cooling and increasing corrosion resistance. In this study, the lubricant TURMOGREASE Li 802 EP, manufactured by Lubricant Consult GmbH, Germany, was employed. This dark brown colored lubricant contained lithium-based thickener to enhance its load-bearing capacity required in rolling and sliding bearings. Its service temperature range (−35 to +140°C) and viscosity were considered appropriate for the assembling application in this study.

3.2 Experimental setup and testing procedure

The locknut used in the machine tools and production facility in the electronic industry could expose to environmental attacks from coolant, etchant, etc. Corrosion developed in the locknut deteriorates with the duration of exposure. In order to accelerate the testing process, an immersion corrosion test of the locknut in 5% NaCl solution following the ASTM B895 Standard [19] was adopted in this study. Three different immersion durations (1, 2, and 4 h) of the locknut were used to simulate different degrees of corrosion. Before the assembling of the locknut on the standard bolt, both components were first cleaned thoroughly with diesel fluid and dried with hot air. They were further cleaned in an ultrasonic container filled with distilled water. After the ultrasonic cleaning, the specimens were dried to remove the residual water. Finally, reagent grade alcohol was employed to remove possible contamination from their surface. A layer of TURMOGREASE Li 802 EP lubricant was applied to the cleaned thread surfaces right before the assembling.

Figure 3 presents the schematic diagram of the experimental setup for measuring the tightening and loosening characteristics of the locknut on the standard bolt. The standard bolt was secured to the fixture frame first. The locknut inserted to a special socket was then aligned coaxially with the standard bolt and driven to rotate by a gear reducer. The applied torque to the locknut was measured by a torque transducer installed between the socket and the gear reducer. A load cell installed at the other fixed end of the standard bolt measured the corresponding induced axial loading. Both the driving torque and the corresponding axial force were recorded in a data acquisition system during the tightening and loosening cycle.

The assembling and testing of the locknut followed the procedures described in the ISO 2320 Standard [20]. Five complete tightening and loosening cycles to a maximum axial force of 14 900 N need to be performed before the formal assembling of the locknut to the designated axial force of 9800 N. During the tightening or loosening process, a constant rotation speed of 4 rpm for the locknut was maintained. The measured torque–axial force data for each specimen under tightening and loosening processes were analyzed to calculate the performance parameters introduced in Section 2.

4. DISCUSSION

4.1 Applied torque and resulting axial force

Figure 4 presents the curves of the measured torque with respect to the induced axial force for the pristine specimens during their first loading–unloading cycle. As the tightening torque first increased, the induced axial force increased accordingly. However, at certain point of loading, a quick drop and recovery in the measured torque, which caused a jerk in the loading curve as seen in Fig. 4b, was observed. This jerked motion in the loading should be related to the stick-slip of friction between contact surfaces. When the loading continued to increase as seen in Fig. 4a, no jerked motion was measured until the preset axial force was reached. In the unloading process, a lower torque than the maximum tightening one was needed to initiate the loosening. This was because the component of axial force was in direction of favoring the loosening motion, in contrast to its opposite role during loading. A quicker descent in slope of the torque–axial force curve was also noted near the start of unloading. It is believed that the gradual transition from static friction to dynamic friction was the plausible reason for this nonlinear response.

Similar test result for a specimen after 4-h corrosion is presented in Fig. 5. Jerked motion during the early loading process was also measured. Moreover, there was an abrupt drop in measured torque at larger tightening loading. The phenomenon was
different from the aforementioned jerked motion at lower loading because the torque was not immediately recovered. More tightening was required to increase the torque at larger axial force after the quick drop. The abrupt decrease in tightening torque should be related to the shear tearing of the oxide layer from the corroded surface. Particulate debris was found after disassembling the locknut at the end of the testing cycle. Upon unloading in loosening, torque larger than the maximum one during tightening to the preset axial force was required to start the rotation of locknut. The increase in roughness and mechanical interlocking between the contact surfaces due to corrosion was considered to be the main cause of this increase. Under the same preset axial force, the required tightening torque was found to decrease with the number of loading–unloading cycles and became nearly steady after five cycles. These results will be presented and discussed afterward.

Figure 6 presents the measured torque and axial force curves of the first six consecutive loading–unloading cycles for a pristine specimen without corrosion treatment. In the tightening measurements, the aforementioned stick-slip jerks at the start of loading were observed for each cycle. Moreover, the torque required for the specified axial force decreased first with the number of cycles and became stable after two cycles. The running-in between the mated thread surfaces during first several loading cycles appeared. As for the loosening cycles in Fig. 6b, the measured torque–axial force behavior became stable only after the first cycle. All the curves showed a slight nonlinearity at the beginning of the unloading process. This result should be related to the transition of the contact surfaces from static friction to dynamic friction. Similar phenomenon was seen, although less obvious due to smaller loading magnitude, at the start of tightening curves shown in Fig. 6a. It must be reiterated again that the curve for the sixth cycle was shorter than the previous five cycles simply because of the smaller axial force tested for this formal cycle as required by the ISO 2320 Standard.

Similar measured results are presented in Fig. 7 for a specimen with 4-h immersion corrosion treatment. Figure 7a shows the aforementioned abrupt drops in the loading processes of first three cycles, which happened at different loading points. Unlike the pristine specimen, the measured torque–axial force behavior did not become stable until five cycles. Nevertheless, the torque decreased with the number of loading cycles as the pristine specimen due to running-in of mating surfaces. More variance in the loosening torques was seen in the unloading cycles, as shown in Fig. 7b. Abrupt drops in loosening torque were observed for all cycles. As seen from the debris after disassembling, the sudden delamination of the oxide layer from the substrate due to discontinuous friction contact of the roughened surfaces should be responsible for this behavior.

### 4.2 Anti-loosening ratio

The anti-loosening test of the locknut was carried out by following the ISO 2320 Standard. The standard requires five initial loading–unloading cycles at larger axial force before the formal test cycle at nominal axial force. The formal test was assigned as No. 6 test in the results reported. According to the size of the
Influence of corrosion on tightening and anti-loosening properties of flank-locking precision locknut

Figure 6 The measured first six consecutive loading–unloading cycles for a pristine specimen without corrosion treatment: (a) tightening and (b) loosening.

Figure 7 The measured first six consecutive loading–unloading cycles for a specimen with 4-h immersion corrosion treatment: (a) tightening and (b) loosening.

Table 1 Anti-loosening ratios of the locknut under the influence of corrosion and repeated cycle of testing.

| Duration of corrosion | Number of loading–unloading cycles |
|-----------------------|-----------------------------------|
|                       | 1   | 2   | 3   | 4   | 5   | 6   |
| 0 h                   | 0.959 | 0.962 | 0.974 | 0.972 | 0.937 | 0.977 |
| 1 h                   | 0.965 | 0.970 | 0.984 | 0.999 | 0.971 | 0.979 |
| 2 h                   | 1.058 | 0.986 | 0.999 | 1.001 | 0.979 | 0.985 |
| 4 h                   | 1.056 | 0.989 | 0.982 | 0.990 | 0.986 | 0.997 |

locknut used in this study, the initial and nominal axial forces were 14 900 and 9800 N, respectively.

Table 1 presents the anti-loosening ratios of the locknut under the influence of corrosion and repeated cycle of testing. For the pristine locknut, the anti-loosening ratio was all less than 1.0 but close to 1.0. Similar results were obtained for the locknut after 1-h corrosion. However, as the duration of corrosion increased to 2 h, the anti-loosening ratio increased and became > 1.0 at the first loading–unloading cycle. Slight decrease in anti-loosening ratio occurred when higher number of loading–unloading cycles
were performed. More or less the same results were obtained for the 4-h specimen. These results along with their scattering bands are presented in Fig. 8. It is seen clearly that the locknut with >2 h corrosion treatment showed larger anti-loosening ratio than their less corroded counterparts only for the first loading–unloading cycle. After the first run-in test, because the more severe corroded specimens produced intensive debris on the collar and thread surfaces of the locknut, the disassembled specimen was cleaned with copper brush. Therefore, the anti-loosening ratio became steadier after the first cycle. Generally speaking, the 2- and 4-h corrosion-treated locknuts still showed slightly higher anti-loosening ratio than the 1-h and pristine counterparts. Moreover, the more corroded specimens showed larger deviations in the measured results, especially for the first few cycles. The more diversified surface morphology for the more corroded specimen than the pristine one, as seen in Fig. 9, could generate different contact conditions between the contact pair. After several run-in test cycles, the locknut can diminish its surface morphology difference by the surface wear. Therefore, the data scattering in the measured results decreased accordingly.

### 4.3 Torque constants

As defined previously in Eqs (1) and (2), the torque constant denotes the proportional constant between the applied torque and the induced axial force in a bolt/nut pair while tightening or loosening. With the known torque constant, the required torque for generating a certain axial force in the bolt/nut assembly can be calculated. However, the relationships described in Eqs (1) and (2) are based on the assumption of linear system. Therefore, the torque constants were calculated based on the least-squares fit of the measured torque–axial force curve such as those presented in Fig. 4. As for the measured curve with abrupt drop such as in Fig. 5, the segment away from the abrupt drop still demonstrated closely linear behavior and had more or less the same magnitude before and after the drop. Thus, the reported torque constant was taken from the lower linear segment of the measured curve for simplicity in calculation.

Table 2 presents the calculated torque constants of the locknut under the influence of corrosion and repeated cycle of testing. It is seen that the torque constant of tightening was higher than its loosening counterpart. Although the torque constant decreased with the number of loading–unloading cycles, the difference between tightening and loosening remained nearly unchanged. As mentioned previously, the difference in the tightening and loosening torques was attributed to the component of the axial force that remained unchanged while the friction force reversed its direction upon loading and unloading processes. Without significant alteration in the thread dimensions and friction coefficient, same difference at each loading and unloading process can be expected from theoretical point of view. These results of torque constants along with the measured scattering data are further shown in Fig. 10. Corroded specimens showed slightly more decrement in torque constants than their pristine counterpart when number of testing cycles increased. Moreover, the more severely corroded specimens, i.e. 2- and 4-h specimens, had

![Figure 8](https://academic.oup.com/jom/article-figures/10.1093/jom/ufaa014/6015293)

**Figure 8** The influence of corrosion duration on the anti-loosening ratio of the locknut.

![Figure 9](https://academic.oup.com/jom/article-figures/10.1093/jom/ufaa014/6015293)

**Figure 9** Photographs of the thread surfaces after the loading–unloading cycle of different specimens: (a) 0 h and (b) 4 h.
Table 2 Torque constants of the locknut under the influence of corrosion and repeated cycle of testing.

| Duration of corrosion | Torque constants | Number of loading–unloading cycles |
|-----------------------|------------------|-----------------------------------|
|                       |                  | 1 | 2 | 3 | 4 | 5 | 6 |
| 0 h                   | \( K \)          | 0.193 | 0.181 | 0.175 | 0.172 | 0.170 | 0.168 |
|                       | \( K' \)         | 0.164 | 0.154 | 0.154 | 0.152 | 0.151 | 0.147 |
| 1 h                   | \( K \)          | 0.216 | 0.197 | 0.182 | 0.174 | 0.170 | 0.168 |
|                       | \( K' \)         | 0.186 | 0.173 | 0.165 | 0.157 | 0.153 | 0.145 |
| 2 h                   | \( K \)          | 0.230 | 0.223 | 0.202 | 0.198 | 0.189 | 0.185 |
|                       | \( K' \)         | 0.201 | 0.191 | 0.176 | 0.181 | 0.175 | 0.161 |
| 4 h                   | \( K \)          | 0.228 | 0.208 | 0.198 | 0.191 | 0.183 | 0.181 |
|                       | \( K' \)         | 0.199 | 0.187 | 0.184 | 0.174 | 0.168 | 0.163 |

Figure 10 The influence of corrosion duration on the torque constants of the locknut.

higher torque constants, \(~10\%\) increment, than the 1-h and pristine ones. More corroded specimens also revealed larger scattering in the calculated torque constants, which coincided with the result of anti-loosening ratio presented in Fig. 8.

5. CONCLUSIONS

The locknut under immersion corrosion in NaCl solution revealed accelerated corrosion with respect to the immersion durations. A more significant increase in surface attack of the locknut by the solution was observed after 4-h immersion treatment. Because of the random surface attack nature of the solution, five preliminary assembling and disassembling cycles of the locknut following the procedures described in the ISO 2320 Standard were demonstrated to be beneficial for obtaining a stable test result. With the influence from immersion corrosion, the variation in the measured torques increased with the duration of corrosion treatment. The formation of surface oxide layer and more corroded surface with higher roughness peaks and valleys provided the possibility of sudden delamination of the local oxide layer from its substrate. Therefore, an abrupt drop in torque was measured during the tightening process for those specimens with duration of corrosion treatment larger than 2 h. Moreover, this corroded surface morphology generated more mechanical interlocking between the contact surfaces, and an anti-loosening torque ratio \( >1 \) was obtained for the first loading–unloading cycle. After the first loading–unloading cycle, the friction wear rendered the contacting surfaces with more or less flattened surface morphology. Therefore, the anti-loosening torque ratio became \( <1 \). Nevertheless, the torque constant in loosening was always smaller than that in tightening. A nearly 10% increase in the torque constants was obtained for the 2- and 4-h treated locknuts compared with their pristine and 1-h treated counterparts. It should be noted that although the anti-loosening torque ratio slightly increased with corrosion, which may be a plus in anti-loosening performance of the locknut, other effects associated with corrosion such as increased performance variance, strength reduction and fatigue sensitivity could lower the overall performance of the locknut.

ACKNOWLEDGEMENT

The financial support from the Ministry of Science and Technology, Taiwan for this study is gratefully acknowledged.

REFERENCES

1. Dragoni E. Effect of thread pitch and frictional coefficient on the stress concentration in metric nut–bolt connections. Journal of Offshore Mechanics and Arctic Engineering 1994;116:21–27.
2. Kenny B, Patterson EA. Load and stress distribution in screw threads. Experimental Mechanics 1895;25:208–213.
3. Bhattacharya A, Sen A, Das S. An investigation on the anti-loosening characteristics of threaded fasteners under vibratory conditions. Mechanism and Machine Theory 2010;45:1215–1225.
4. Sase N, Nishioka K, Koga S, Fujii H. An anti-loosening screw-fastener innovation and its evaluation. Journal of Materials Processing Technology 1996;77:209–215.
5. Sase N, Fujii H. Optimizing study of SLBs for higher anti-loosening performance. Journal of Materials Processing Technology 2001;119:174–179.
6. Eccles W, Sherrington I, Arnell RD. Frictional changes during repeated tightening of zinc plated threaded fasteners. Tribology International 2010;43:700–707.
7. Zhao H. Stress concentration factors within bolt–nut connectors under elasto-plastic deformation. International Journal of Fatigue 1998;20:651–659.
8. Hubbertz H, Friedrich C. Friction behavior and preload relaxation of fastening systems with composite structures. Composite Structures 2014;110:335–341.
9. Baragetti S, Terranova A, Vimercati M. Friction behavior evaluation in beryllium–copper threaded connections. International Journal of Mechanical Sciences 2009;51:790–796.
10. Izumi S, Yokoyama T, Iwasaki A, Sakai S. Three-dimensional finite
    element analysis of tightening and loosening mechanism of threaded
    fastener. *Engineering Failure Analysis* 2005;12:604–615.
11. Esaklul KA, Martin JW. High Strength Fasteners for Subsea Applica-
    tions. No. 04151, NACE International, Houston, TX, 2004.
12. Harrison TJ, Crawford BR, Brandt M, Clark G. Modelling the effects
    of intergranular corrosion around a fastener hole in 7075-T651 alu-
    minum alloy. *Computational Materials Science* 2014;84:74–82.
13. Esaklul KA, Ahmed TM. Prevention of failures of high strength fas-
    teners in use in offshore and subsea applications. *Engineering Failure
    Analysis* 2009;16:1195–1202.
14. Jha AK, Manwatkar S, Sreekumar K. Hydrogen-induced intergranu-
    lar stress corrosion cracking (HI-IGSCC) of 0.35C–3.5Ni–1.5Cr–
    0.5Mo steel fastener. *Engineering Failure Analysis* 2010;17:777–786.
15. Zelinka SL, Derome D, Glass SV. Combining hygrothermal and cor-
    rosion models to predict corrosion of metal fasteners embedded in
    wood. *Building and Environment* 2011;46:2060–2068.
16. Majzoobi GH, Farahi GH, Habibi N. Experimental evaluation of the
    effect of thread pitch on fatigue life of bolts. *International Journal of
    Fatigue* 2005;27:189–196.
17. Chen CM, Sun CH. A study of surface characteristics of flank lock
    type precision locknut under a vertical installation. *Journal of Me-
    chanics* 2018;34:47–58.
18. Chen CM, Sun CH. Thread profile and wear properties of flank
    lock type precision locknut while suffering from preload. *Interna-
    tional Journal of Advanced Scientific and Technical Research* 2015;3:
    97–113.
19. ASTM B895. Standard Test Methods for Evaluating the Corrosion Re-
    sistance of Stainless Steel Powder Metallurgy (PM) Parts/Specimens by
    Immersion in a Sodium Chloride Solution. ASTM International, West
    Conshohocken, PA, 2016.
20. ISO 2320. *Fasteners: Prevailing Torque Steel Nuts: Functional Prop-
    erties*. International Organization for Standardization, Geneva,
    Switzerland, 2015.