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Optimum Design of Thin Walled Tube on the Mechanical Performance of Super Lock Nut*

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Abstract
The bolts and nuts are widely used in various fields as important joining elements with long history. However, loosening induced by the vibration and external loads is still a big problem. For example, the loosening sometimes causes very serious accident without notice. This paper deals with a special nut named "Super Lock Nut (SLN)" which can prevent loosening effectively. There is a thin walled tube between the upper and lower threads, which can be deformed along the axial direction so that the phase difference of lower and upper threads is produced and SLN is developed. This phase difference induces the contrary forces on the surfaces of the upper and lower threads, which bring out the anti-loosening performance. In this study, the anti-loosening performance is analyzed and realized with the finite element method. Moreover, the anti-loosening performances under various phase difference of lower and upper threads are compared and finally best dimensions for SLN are examined.

Key words: Optimal Design, Plastic Working, Machine Element, Press Working, Analytical Model, Anti-Loosening, Thin Walled Tube, Prevailing Torque

1. Introduction

Threaded connections play a critical role in engineering with long history. Because of their relatively low cost and easy disassembly for maintenance, they are widely used for mechanical products and structures in modern times. However, self-loosening is one of the most frequent failure modes for threaded connections, brings out the failure of engineering products and several serious accidents. Therefore, in recent years much attention has been paid to the research on the anti-loosening.

Many experiments have been performed in order to find out the reasons and the influence factors of self-loosening. The loosening is mainly due to external shear load, which is perpendicular to the axis [1, 2]. In the previous studies [3, 4], it is shown that slight loosening is caused by the slip of the bolt head. And in Ref. (5), it is found that the loosening is caused by a twist caused by a relative slip between the male screws and the female screws and a slackening of the bolt torsion between the bearing surfaces. With the recent development of the computer, Finite Element Method (FEM) is widely used on these types of research [6, 7].

The Super Lock Nut (SLN) [8] and the Super Stud Bold (SSB) [9] as shown in Fig.1 are developed in order to prevent self-loosening. In this study, the capability of the anti-loosening will be investigated using FEM and the optimization of the original dimension will be discussed. The FEM results will be examined and compared with experimental results [10].

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Fig.1 (a) Super lock nut (b) Super stud bolt

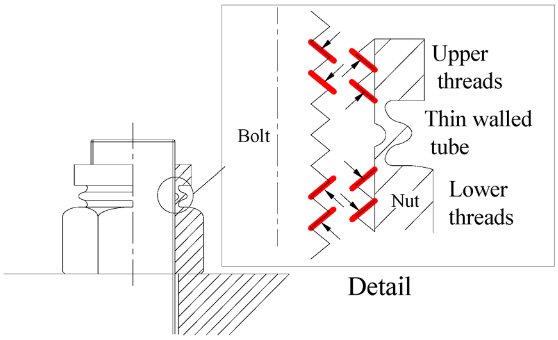


Fig.2. Anti-loosening mechanism

2. Anti-loosening principle of the Super Lock Nut

In the anti-loosening mechanism, the thin walled tube between the upper threads and the lower threads plays an important role as Fig.2 shows. The thin walled tube can be deformed along the axis, and the phase difference of lower and upper threads is designed in the course of processing. Accordingly, the deformation must be produced in order that the threads meet each other in the course of fastening. Then, the thread contact force shown in Fig. 2 comes out due to this deformation. This force is called the griping force, by which the prevailing torque is produced, so that the self-loosening can be prevented. The working principle of the Super Stud Bold (SSB) is very close to that of the Super Lock Nut (SLN). In this paper the SLN is taken as a sample, and the best dimensions will be discussed. Also, the capability of the anti-loosening will be investigated using FEM and the results will be compared with experimental results. Both courses of processing and fastening will be simulated, and the relation between axial force and displacement will be researched. Through the comparison for anti-loosening capability, the reasonable range of the phase difference of lower and upper threads will be decided. Since the thin walled tube is the heart of anti-loosening mechanism, best original dimensions will be discussed in this study.

3. Notation

In this paper the following notations will be used.

L, $L_1 \sim L_5$	*Length of the thin walled tube defined in Fig. 5 and Fig. 6 (mm)*
R	*Curvature radius of the thin walled tube defined in Fig. 3 (mm)*
t	*Thickness of the thin walled tube defined in Fig. 3 (mm)*
z	*Forced displacement defined in Fig. 3 (mm)*
P	*Pitch of nut (mm)*
b, b'	*Spring back length defined in Fig. 5 and Fig. 6 (mm)*
α, $\alpha_1 \sim \alpha_5$	*Phase difference of lower and upper threads defined in Fig. 5 and Fig. 6*
h, $h_1 \sim h_5$	*Height of nut defined in Fig. 5 and Fig. 6 (mm)*
$\boldsymbol{\sigma}_z$	*Axial stress (MPa)*
ε_z	*Axial strain*
$\boldsymbol{k}$	*Spring factor (N/m)*
$\boldsymbol{Ts}$	*Prevailing torque (N·m)*

4. Analysis model and method

4.1. Analysis model

As shown in Fig.3 (a), the SLN is simplified into an axi-symmetric model to be studied. Here the bottom is fixed, while the forced displacement *z* (mm) is placed on the top of the model by the rigid body. In this study, the thin walled tube is mainly researched with the finite element method as Fig.3 (b) shows.

The material of the SLN is S20C (JIS), whose stress-strain relation in Fig.4 is used in the elastic-plastic finite element analysis of the thin walled tube. Here, Young's modulus is 210GPa, Poison's ratio is 0.3, and the yielding stress is 289MPa.

4.2. Analysis method

Using the axi-symmetric FE model, both courses of processing and fastening-loosening of SLN are simulated. The processing course is shown in Fig. 5, and the course of fastening-loosening is shown in Fig.6. In the Fig. 5 (a), the length L of thin walled tube is produced on the top of normal nut by machining. At this time, the phase difference of lower and upper threads is 0. As shown in Fig. 5 (b), the thin walled tube is pressed by (p-α) mm. Here, *α* (mm) is the nominal phase difference of lower and upper threads, which is smaller than the pitch of nut (p=2mm). When the press is removed, spring back happens as shown in Fig. 5 (c). Here, L_1=L-(p-α) and L_2=L-(p-α)+b, so that the real phase difference of lower and upper threads α_2=α+b=p-(L-L_2) appears. Figure 6 (d) is the same as Fig. 5 (c), and Fig. 6 (e) shows the phase difference of lower and upper threads becomes 0 because the threads of the bolt and nut can meet each other while the nut is fastened. In Fig. 6 (f), spring back b′happens after loosening. In order to simulate both courses, which include large plastic strains, elastic-plastic large deformation theory will be applied in this analysis.

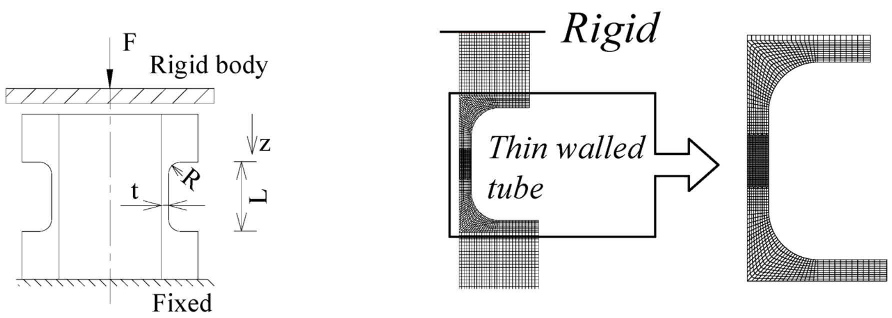


Fig.3 (a) Analysis model (b) Finite element model (c) Detail of thin walled tube

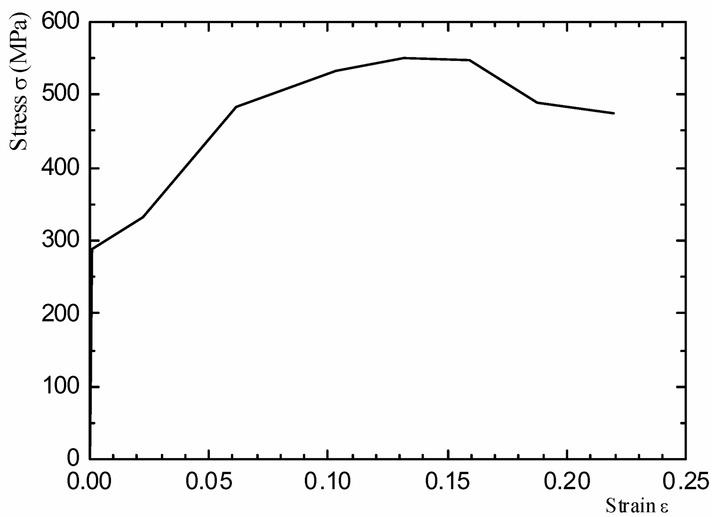


Fig.4. Relation between stress and strain

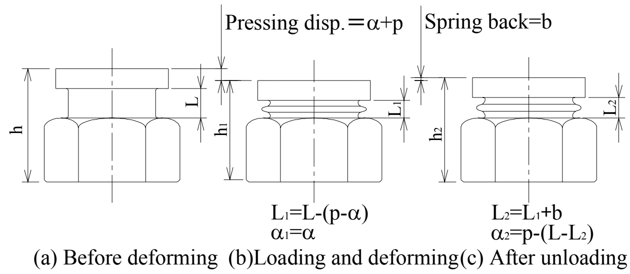


Fig.5. Dimension change in the course of processing

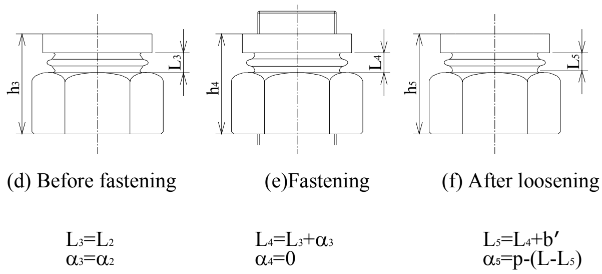


Fig.6. Dimension change in the course of fastening-loosening

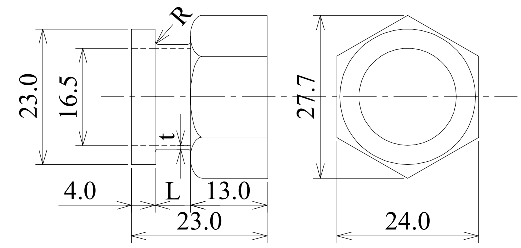


Fig.7. Initial dimension of M16 SLN

5. Analysis results

5.1. The anti-loosening capability

A standard model M16 nut is employed, and the dimension of the thin walled tube is shown as Fig.7, here, L=6mm, R=0.5mm and t=0.65mm.

In order to design the phase difference of lower and upper threads (α=0.4mm), the forced displacement 2.4mm is assumed from the experimental data; then the FEM results are compared with the experiment. The dimensions of SLN in the courses of processing and fastening-loosening are shown in Table 1 and Table 2, respectively.

Table 1 and Table 2 indicate that the experimental and EFM results are in good agreement although experimental data may include some measuring errors. Because of the spring back (FEM: 0.036mm, Experiment: 0.048mm), the real phase difference of lower and upper threads (FEM: 0.364mm, Experiment: 0.344mm) differs from the nominal phase difference of lower and upper threads (α=0.4mm).

For the dimensions L=6.0mm, R=0.5mm and t=0.65mm, the relation between the axial force and the displacement is shown in Fig.8. The course of processing is indicated as the line (a) → (b) →(c); then, the final displacement 2.36mm provides the real phase difference of lower and upper threads 0.36mm. The line from (d) to (e) shows the course of fastening, and the line from (e) to (f) shows the course of loosening. In those loading and unloading courses, the plastic deformation occurs and the permanent deformation 2.36-2.04=0.32mm has been added. Then, only small phase difference of lower and upper threads (2.04-2.00=0.04mm) remains. However, in consecutive fastening-loosening courses, the

Table1. Dimensions in the course of processing (L=6mm, R=0.5mm, t=0.65mm)

	FEM	Experiment
Height before deforming h [mm] in Fig. 5	23.000	23.009
Height while deforming h_1 [mm] in Fig. 5	20.600	20.617
Height while unloading h_2 [mm] in Fig. 5	20.636	20.765
Spring back b [mm] in Fig. 5	0.036	0.048
Phase difference of lower and upper threads α[mm] in Fig. 5	0.364	0.344

Table2. Dimensions in the course of fastening and loosening (L=6mm, R=0.5mm, t=0.65mm)

	FEM	Experiment
Height before fastening h_3[mm] in Fig. 6	20.636	20.765
Height while fastening h_4[mm] in Fig. 6	21.000	20.831
Height after loosening h_5[mm] in Fig. 6	20.967	20.788
Permanent deformation h_5-h_3[mm] in Fig. 6	0.331	0.023
Prevailing torque Ts [N·m]	14.60	16.00

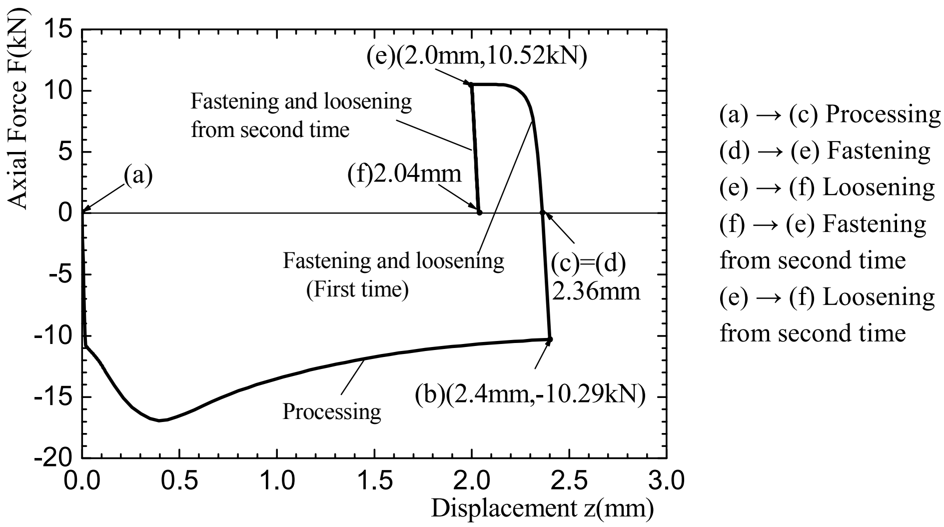


Fig.8. Relation between axial force and displacement (L=6.0mm, R=0.5mm)

relation between the axial force and the displacement moves to the line from (f) to (e). Because the deformation in this course is totally elastic, plastic deformation does not occur and the phase difference of lower and upper threads 0.04mm will not be changed anymore. Moreover, the axial force 10.52kN is also unchanging, and therefore, the prevailing torque is the same in the consecutive fastening-loosening courses.

From Fig. 8, it can be shown when the threads meet each other (Fig. 8(d)), the axial force is 10.52kN. Accordingly, the prevailing torque of SLN can be computed by Eq.(1)[11].

$$T = \frac{d_2}{2} F \tan\rho' + \frac{d_2}{2} F \tan\beta + \frac{d_w}{2}\mu_w F \qquad (1)$$

Where F is axial force,
d is the radius of screw, and approximately $d_2 = 0.92\, d$, $d_w = 1.3\, d_2$,
ρ' is friction angle between the threads, here $\tan(\rho')=0.15$
β is lead angle of threads, 2.4796 (deg)
μ_w is average friction factor on the interface between the head of bolt and the clamp.

The prevailing torque is the fastening torque when the bottom surface of the bolt head does not contact with the upper surface of the clamped body. Therefore we can put the third term in Eq.(1) is 0, and the prevailing torque may be evaluated as Ts=14.97 N·m.

5.2. Anti-loosening capability under various phase difference of lower and upper threads

Since the phase difference of lower and upper threads of the SLN controls the capability of anti-loosening, the effect of the phase difference on the spring factor is studied, and suitable dimensions are discussed.

If the axial force is too small, the anti-loosening capability is little; on the other hand, while the axial force is too large, fastening becomes difficult. Therefore, there is a certain range of the suitable axial force ΔF which can prevent self-loosening effectively (see Fig. 9). In Fig.9, when the spring factor is k_1, the range of the phase difference of lower and upper threads α_1 should be in $\Delta\alpha_1$; while the spring factor is k_2 ($<k_1$), the range of the phase difference of lower and upper threads α_2 should be in $\Delta\alpha_2$; then, $\Delta\alpha_1 < \Delta\alpha_2$. That is to say, the suitable range of the phase difference of lower and upper threads becomes wider if spring factor is smaller. Usually of SLN includes some error of the phase difference in the course of processing, small spring factors may be desirable.

In Table 3, initial dimensions of SLN are fixed as L=6mm, R=0.5mm, and t=0.65mm. Then, different forced displacements are applied in order to attain various phase difference of lower and upper threads.

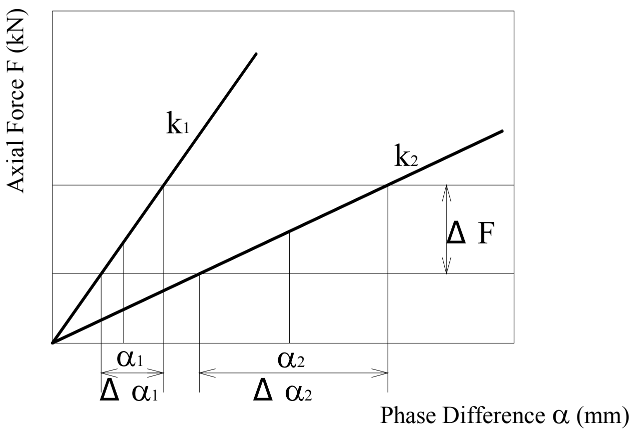


Fig.9. Relation between the axial force and phase difference of lower and upper threads

Table 3 Results of different forced displacements (L=6mm, R=0.5mm, t=0.65mm)

Forced displacement z[mm]	2.40	2.20	2.14	2.10
Phase difference of lower and upper threads α[mm]	0.36	0.16	0.10	0.06
Spring factor $k\times10^8$ [N/m]	3.048	3.068	3.050	3.077
Axial force F [kN]	10.26	10.33	9.76	8.62
Prevailing torque Ts [N·m]	14.60	14.70	13.88	12.26

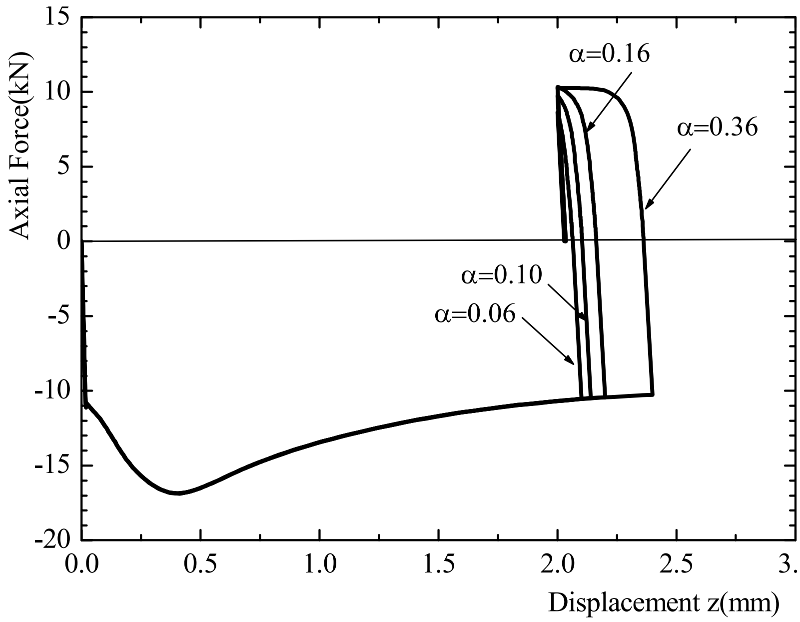
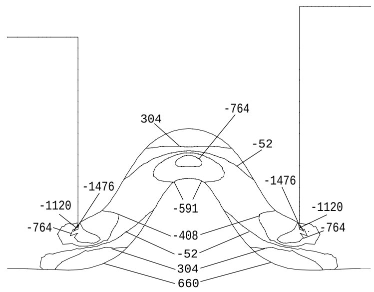
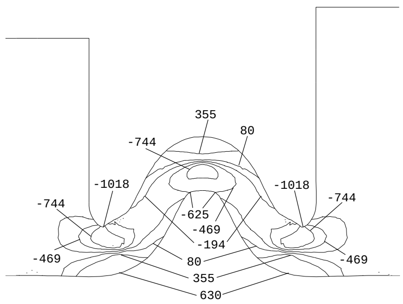


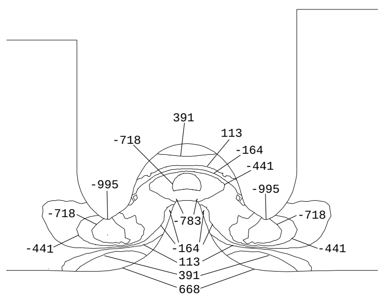
Fig.10. Relation between axial force and displacement under various phase different (L=6mm, R=0.5mm, t=0.65mm)



(a) R=0



(b) R=0.5mm



(c) R=1.0mm

Fig.11. Axial stress distribution $\boldsymbol{\sigma_z}$ (L=6.0mm, t=0.65mm)

It is seen that the spring factor is almost equal when the phase difference of lower and upper threads is changed. Also, the prevailing torque is nearly constant when the phase difference of lower and upper threads is larger than 0.10. Figure 10 shows the relation between the axial force and the displacement under various phase difference.

With increasing the phase difference of lower and upper threads α, the plastic deformation becomes larger when the nut is fastened. Accordingly, considering the error in the course of processing, it may be concluded that the phase difference of lower and upper threads should be designed in the range of 0.1mm~0.15mm.

5.3. Influence of the dimension of the thin walled tube on the anti-loosening capability

The thin walled tube is the heart of SLN because the dimension has large influence on the anti-loosening capability, stress distribution and spring factor. In this study, the inference of the dimensions *R*, *L*, *t* in Fig. 7 will be investigated, and best dimensions will be examined.

(a) Influence of curvature radius *R*

In order to improve stress distribution at both ends of thin walled tube, the effect of curvature radius *R* in Fig. 7 is studied. As shown in Fig. 7, L and t are fixed as L=6.0mm, t=0.65mm, and *R* is changed. When *R* is 0.0, 0.5, 1.0, the stress distributions of the thin walled tube in Fig. 5 (b) are shown in Fig.11 (a), (b), (c), respectively.

From Fig. 11, while *R* is smaller, the stress concentration is more serious at both ends of the thin walled tube. Conversely, while *R* is larger, at the center of the thin walled tube the stress become larger. The stress distribution is the most desirable in Fig. 11 (b) while *R* is 0.5mm. Figure 12 shows the relation between the axial force and the displacement for R=0.0, 0.5, 1.0mm. It is seen that the curvature radius has little influence on the anti-loosening capability.

(b) Influence of length of the thin walled tube *L*

To investigate the effect of length *L*, dimensions *R* and t are fixed as R=0.5mm, t=0.65mm, and *L* is changed (see Fig. 7). When *L* is 5.0, 6.0, 8.0, the results are shown in Table 4.

As Table 4 shows, while *L* is longer, the spring factor becomes smaller, and spring back b in Fig. 5 becomes larger. Here, spring back b may be regarded as an amount of elastic deformation. It should be noted that this elastic deformation is much smaller than the phase difference of lower and upper threads (0.1~0.15mm). In other words, large plastic deformation always exists in the course of first fastening-loosening shown in Fig.13 whenever L is 5, 6 or 8mm.

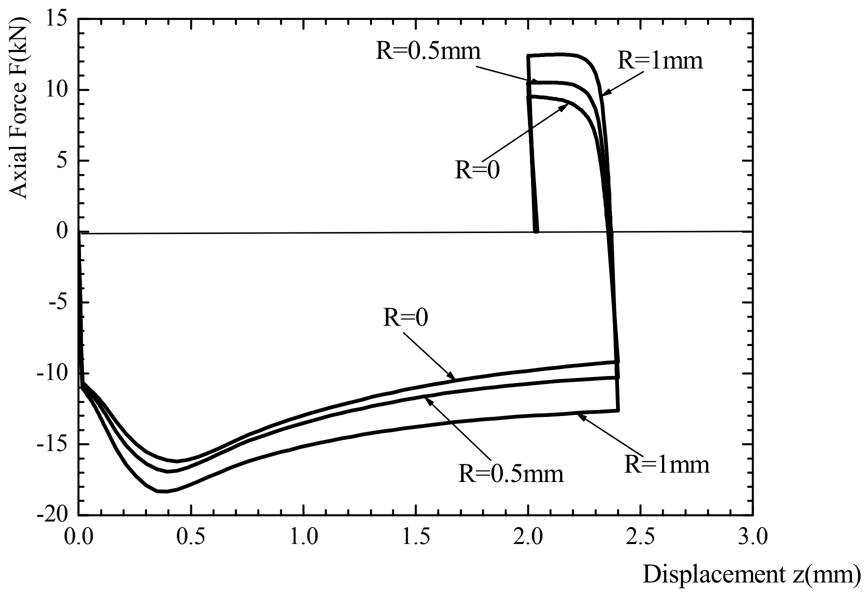


Fig.12. Relation between axial force and displacement (L=6.0mm, t=0.65mm)

Table 4 Dimensions and character in the course of fastening (R=0.5mm, t=0.65mm)

Length of thin walled tube L[mm]	5	6	8
Permanent deformation L_5-L_3[mm]	0.347	0.331	0.303
Spring factor k ×10^8[N/m]	5.119	3.048	1.844
Spring back b L_2-L_1[mm] (Elastic deformation)	0.025	0.034	0.045
Prevailing torque Ts [N·m]	18.466	14.967	12.762

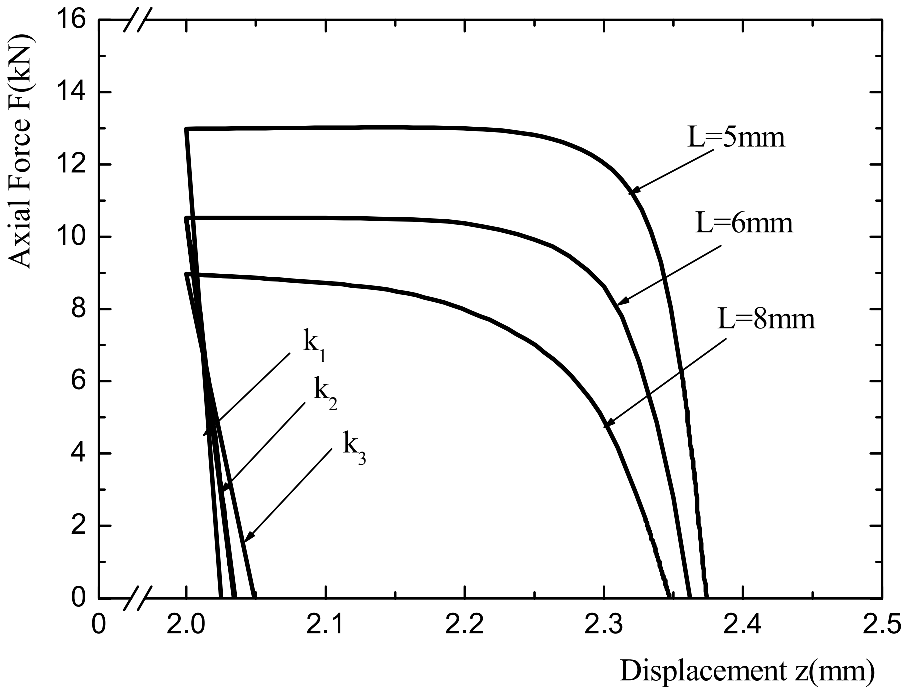


Fig.13. Relation between axial force and displacement (R=0.5mm, t=0.65mm)

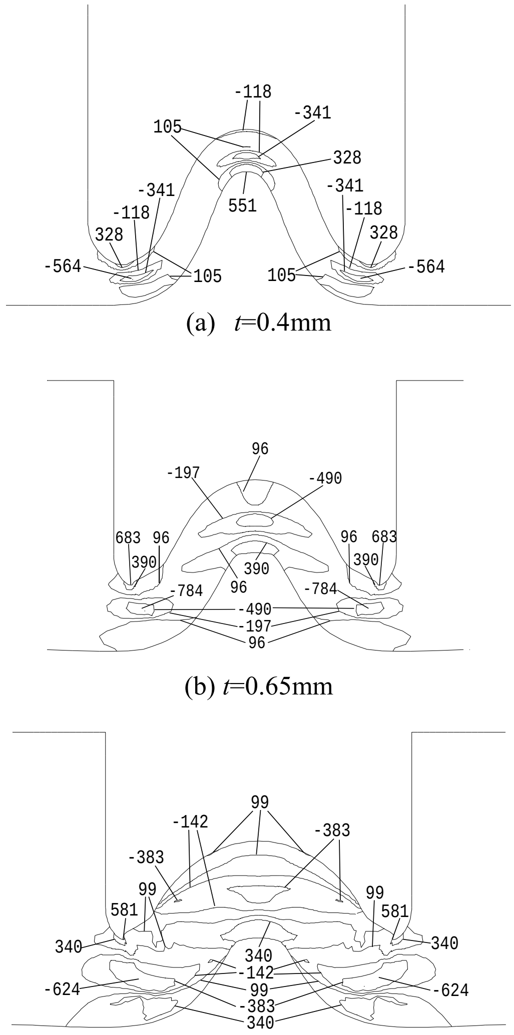
It can be seen that the prevailing torque becomes smaller while L is longer in Table 4. That is to say, the anti-loosening capability becomes lower as L is longer. In addition, the cost of processing is higher when L becomes longer. According to the above, the length of thin walled tube should be designed as short as possible if the thin walled tube can be deformed as show in Fig. 5. It may be concluded that L=5mm is the best.

(c) Influence of thickness of the thin walled tube *t*

In order to improve both processing and fastening courses, the influence of the thickness of the thin walled tube t is studied. While the L and R are fixed, thickness t is changed as 0.4, 0.65, and 0.8mm. The stress distributions σ_z are indicated in Fig. 14 (a), (b) and (c).From Fig.14, it is seen that the stress distribution becomes complicated with increasing the thickness t. The stress distribution of t=0.4mm is desirable, and therefore, it may be concluded that the best thickness t is 0.4mm.

(d) The best dimension

According to the above discussion, the best dimensions of M16 SLN are designed as R=0.5mm, L=5.0mm, and t=0.4mm. The relation between axial force and displacement is shown in Fig.15.



(a) t=0.4mm

(b) t=0.65mm

(c) t=0.8mm

Fig.14. Distributions of $\boldsymbol{\sigma_z}$[MPa]

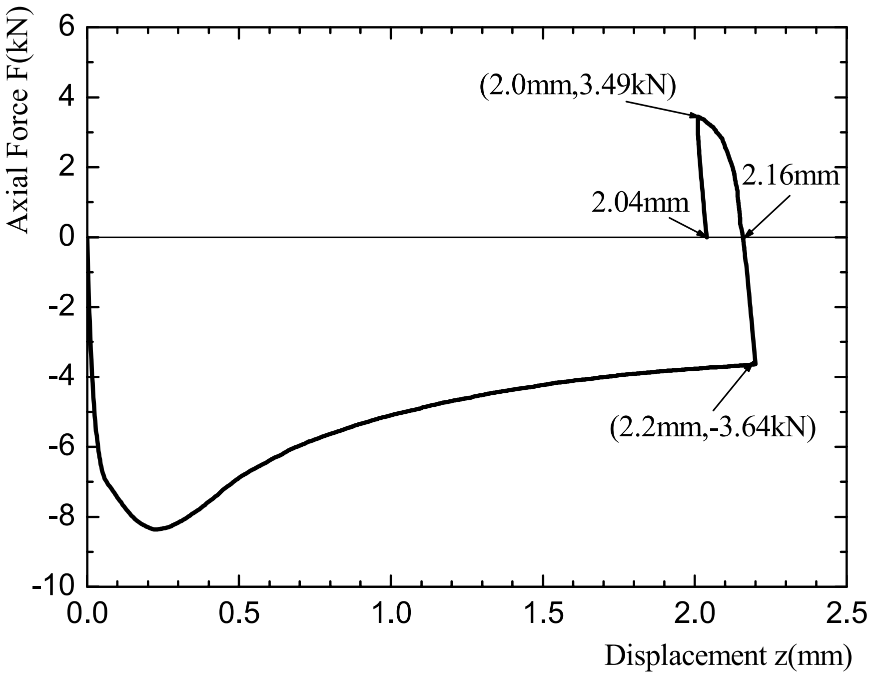


Fig.15. Relation between axial force and displacement
(R=0.5mm, L=5.0mm and t=0.4mm)

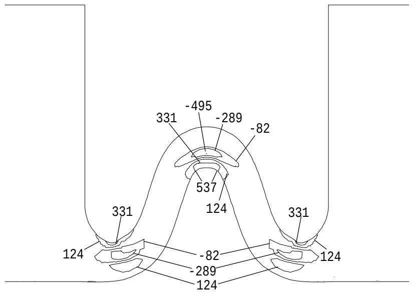


Fig.16. Axial stress $\boldsymbol{\sigma_z}$ distribution
(R=0.5mm, L=5.0mm and t=0.4mm)

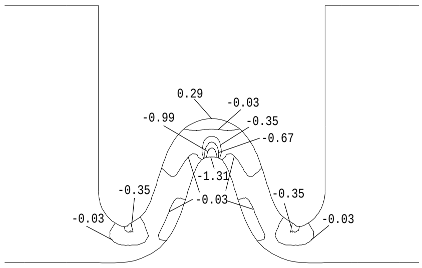


Fig.17. Axial strain ε_z distribution
(R=0.5mm, L=5.0mm and t=0.4mm)

In the course of fastening, the axial force 3.49kN appearing in Fig.15 may cause an anti-loosening capability, whose prevailing torque is 5.0 N·m. Here, the spring factor is 8.73×10^7N/m, which is the smallest in this study. Moreover, the axial stress distribution and the axial strain distribution are shown in Fig.16 and in Fig.17, which are also the most desirable.

6. Conclusions

In this study, "Super Lock Nut (SLN)" which can prevent self-loosening effectively was researched with the application of FEM. The courses of processing and fastening-loosening were simulated, and the relations between the axial force and displacement were discussed. Also the anti-loosening capability was studied though an axi-symmetric FE model. On the basis of the elastic-plastic large deformation theories and experimental results, the following conclusions can be drawn:

(1) The self-loosening is prevented by the prevailing torque 14.60N·m. The FEM results are in qualitative agreement with the experimental results.
(2) Considering the error in the course of processing, it may be concluded that the phase difference of lower and upper threads should be designed in the range of 0.1mm~0.15mm.With increasing the phase difference of lower and upper threads α, the plastic deformation becomes larger when the nut is fastened.
(3) Considering the stress distributions, the spring factor and the anti-loosening capability, the dimensions of the thin walled tube are optimized as R=0.5mm, L=5mm and t=0.4mm.

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