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Development of Anti-Loosening Bolts Based on Innovative Double Thread Mechanism

Teruie Takemasu, Toshinaka Shinbutsu, Shuichi Amano, and Jyo Shimura

Abstract Anti-loosening bolted joints were developed with an innovative double-thread mechanism composed of coaxial single and multiple coarse threads. The number of coarse threads of the multiple-thread was set to 3 (denoted as 3thread DTB-II), and its thread structure was fundamentally modified as follows: (i) one of the three multiple-thread grooves was removed for 3thread DTB-II specimens and one of the two remaining grooves shifted downwards by a half pitch (denoted 3-1thread DTB-IIB) and (ii) the depth of the multiple-thread grooves was reduced by up to 50% of the thread height (denoted 3-1thread DTB-IIC). FEM thread rolling simulations were performed using a dedicated die. The two kinds of modified DTB-II specimens were rolled precisely and the thread heights reached the target value at all cross sections. The forming states in the thread rolling experiments well matched the FEM simulation states. The performance evaluation tests demonstrated that the 3-1thread DTB-IIC specimens had sufficient tensile strength, and its anti-loosening performance exceeds the reference level given in DIN25201.

Keywords Bolted joint · Double thread mechanism · Thread rolling · FEM · Tensile strength · Loosening test

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1 Introduction

It is well known that cyclic stresses or impact loading during service can cause the loosening and fatigue failure of bolted joints, possibly leading to serious accidents [1]. The loosening of bolted joints can be roughly divided into the non-rotational type, in which the axial force decreases without nut rotation, and the rotational type, in which return rotation of the nut occurs [2, 3]. Non-rotational loosening can easily be dealt with by additional tightening of the nut or a design change. In contrast, rotational loosening is an inevitable issue because it occurs suddenly in an environment with cyclic loading, severe vibration, and impact forces. Most commercially available anti-loosening screw parts exhibit macro slip on the nut-bearing surface when subjected to a severe transverse vibration load and cannot completely suppress rotational loosening because most of them only enhance the frictional force between the bolt and the nut or between the nut and the bearing surface [4–7]. In comparison, it has been proven that the double-thread bolted (DTB) joints having two types of coaxial screw thread with different lead angles have an excellent anti-loosening performance [8]. For such joints, a higher lead nut is first fastened, and then a lower lead nut is added to form a double nut structure. The anti-loosening mechanism of DTB is enhanced by a mechanical locking based on the interference effect of two kinds of nut with different loosening speeds.

DTB joints with a very simple structure composed of a single coarse thread and a single fine thread (denoted DTB-I), have been a major research target [9]. However, as DTB-I has become more widely used, various disadvantages associated with the fine screw thread have been pointed out by users, including troublesome torque management for each nut, insufficient strength of the fine thread, high manufacturing cost of rolling dies, and low durability. Bolt fasteners, denoted DTB-II, was then proposed based on an innovative double-thread mechanism composed of a single coarse thread and a multiple coarse thread [10, 11]. Nut fastening and torque management for DTB-II can be performed very easily since the inner multiple-thread nut, mounted first, is also rotated when the outer single-thread nut is tightened, solving most of the problems encountered with the conventional DTB-I. Thread rolling experiments and tensile strength tests were conducted on DTB-II specimens with 2, 3, and 4 threads on the multiple-threads, which were denoted 2, 3 and 4thread DTB-II, respectively, to evaluate the proposed double-thread structure. It is found that 3thread DTB-II formed relatively well, although the height of the screw thread profile of 2 and 4thread DTB-II did not reach the target level. The tensile strength of these DTB-II specimens tended to decrease with increasing number of multiple-threads, and 3 and 4thread DTB-II were damaged by the shear failure of the screw thread even with the double-nut structure. Accordingly, to solve these problems, the authors designed several kinds of modified DTB-II, in which the number of multiple-thread grooves superimposed on the single screw thread was selectively reduced to $m-1$ (m: number of multiple-threads) or fewer from the m-thread DTB-II, manufactured them by thread-cutting, and carried out tensile strength tests. The shear

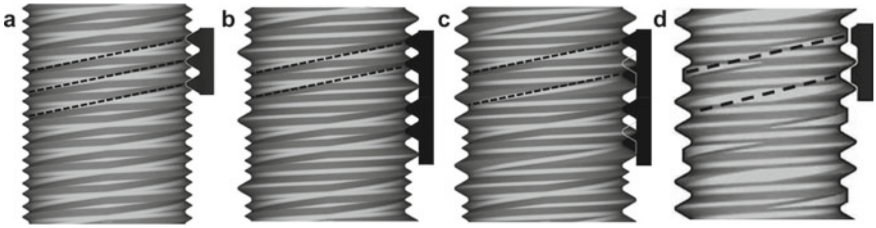

Fig. 1 Diagrams of screw thread structure of **a** 3thread DTB-II, **b** 3-1thread DTB-IIA, **c** 3-1thread DTB-IIB, **d** 3-1thread DTB-IIC

fracture of the screw thread of all DTB-II specimens mounted with double nuts was successfully suppressed by reducing the number of multiple-threads by at least one.

In this study, thread rolling FEM simulations and experiments were conducted on the two types of modified 3thread DTB-II (see below for description) to examine the material deformation state and forming accuracy. Several performance evaluation tests were then performed to determine the effect of the modified screw thread profile on the tensile strength and the anti-loosening performance of those DTB-IIs.

2 Methods

2.1 Screw Thread Structure of Modified DTB-II

Figure 1 shows a comparison of the screw thread structure of 3thread DTB-II [10] and those of the three modified types. Figure 2 shows the changes in the thread cross-sectional area ratio, ξ, of each DTB-II, which was calculated by dividing the thread cross-sectional area of three pitches at each angular position of DTB-II by that of the normal single screw-thread. Figure 1a shows the thread structure of the original 3thread DTB-II, and b shows that of the modified 3-1thread DTB-IIA, in which one thread groove was simply removed from the three thread grooves and the remaining two thread grooves were superimposed onto a single screw thread. With this modification, the minimum value of the thread cross-sectional area ratio, ξ_{min}, increased to approximately 55%, as shown in Fig. 2. However, since there are four consecutive small threads at the groove bottom at the 90° and 270° positions, at which thread shear fracture may initiate, 3-1thread DTB-IIA was excluded from further testing. One of the remaining two thread grooves was shifted downwards by a half pitch to be aligned at an equal pitch, as shown in Fig. 1c; this joint is denoted 3-1thread DTB-IIB or simply DTB-IIB [11]. For 3-1thread DTB-IIA, the complete screw thread appears at only the 0° and 180° positions, whereas 3-1thread DTB-IIB has one or two complete screw threads in three pitches at all cross sections. The ξ value of 3-1thread DTB-IIB changes at the 90° cycle, as shown in Fig. 2, which is half that of 3-1thread DTB-IIA, and ξ_{min} is 70%, which is twice that of 3thread

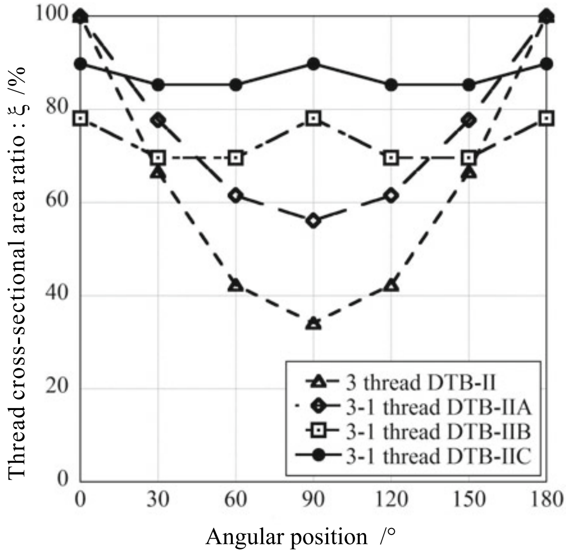

Fig. 2 Comparison of changes in the thread cross-sectional area ratio, ξ, of each DTB-II specimens, which was calculated from the thread cross-sectional area of three pitches at each angular position

DTB-II. However, a small-thread portion remains at the groove bottom for all angular positions, which reduces tensile strength. In order to completely remove these small threads, the depth of the multiple-thread grooves was reduced by up to 50% of the thread height, as shown in Fig. 1d; this joint is denoted 3-1thread DTB-IIC or simply DTB-IIC. With this modification, ξ_{min} increased up to 85% and improvements in tensile strength were expected.

2.2 *FEM Simulation Model and Experimental*

To reduce cost, DTB-II joints have to be manufactured using a mass production process. Thread rolling is most suitable for this task because of its productivity and widespread use. In the thread-rolling of DTB-II, both the single and multiple coarse threads should be formed simultaneously on a single rod axis through one rolling process. To realize this process, the authors developed a dedicated roller die (denoted DTB-II die) with a special groove profile, which has almost the same outline as that of the thread profile of DTB-II specimens in each corresponding cross section. Thread rolling simulations of M12 DTB-IIB and C were first performed using a 3D FEM model to examine the forming process of the screw thread. The commercial FEM code Simufact.forming ver.15 was used. Figure 3a and b show the FEM simulation model, in which the workpiece is an elasto-plastic cylindrical material and the rolling flat dies are rigid bodies. During processing, the two flat dies were moved synchronously in opposite directions (see arrows in the figure) and simultaneously pushed into the workpiece at the same constant speed. The total amount of indentation of the die,

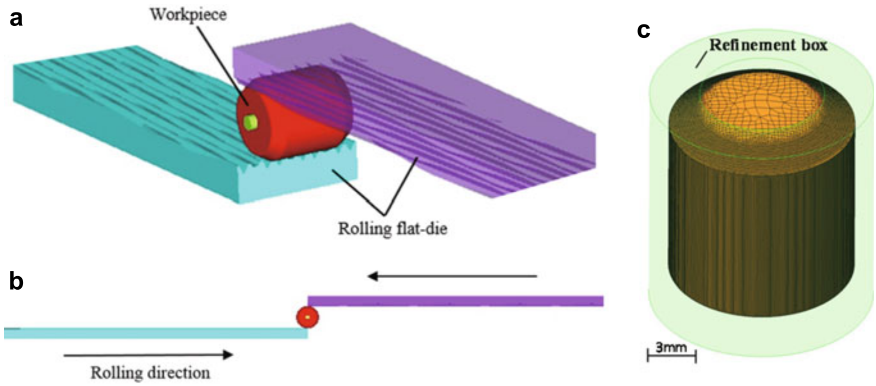

Fig. 3 **a** Perspective view of FEM model. **b** Side view. **c** FEM mesh of workpiece. (Color figure online)

δ_{max}, was set to a prescribed value for each DTB-II (δ_{max} = 0.56 mm for DTB-IIB and δ_{max} = 0.62 mm for DTB-IIC) until the workpiece was rotated 8 times; then, the dwelling process was performed for two rotations. Coulomb's friction law was assumed at the contact interface between the dies and the workpiece, and the coefficient of friction μ was set to 0.2. Figure 3c shows the initial FEM mesh of the workpiece with a diameter of ϕ10.8 mm. A semitransparent refinement box was placed in the region from an inner diameter of 8 mm to an outer diameter of 14 mm; this region is divided by hexahedron fine elements with a reference size of 0.4 mm. The height of the cylindrical workpiece was restricted to the 9-pitch length of a single screw-thread bolt to reduce calculation time and to avoid the effect of edge droop on thread forming around the central portion in the axial direction.

The thread rolling experiments of M12 DTB-IIB and C were conducted using a manual rolling machine with a two-roller die plunge feed (FA-16U, Nissei Co., Ltd.) under a die rotational speed of 62 rpm and a net processing time of 4 s, which included a 1 s dwelling time. The initial diameter of the workpiece and the final amount of the die radial feed were decided based on the screw thread forming state. A low-carbon steel bar made of DIN 17100 was used as the bolt material.

The methods and conditions of the several performance tests are described later.

3 Results and Discussion

3.1 Thread Rolling FEM Simulation and Experiments

Figures 4a and 5b show the equivalent plastic strain distribution, $\bar{\varepsilon}$, of thread-rolled DTB-IIB and C obtained from the FEM simulation, and Figs. 4b and 5b show the outer appearance of the samples used in the experiment, respectively. Figure 6a and b

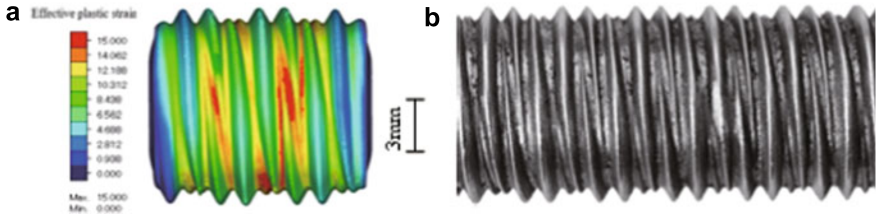

Fig. 4 **a** Equivalent plastic strain distribution of rolled 3-1thread DTB-IIB using FEM. **b** Rolled sample of 3-1thread DTB-IIB used in experiment. (Color figure online)

compare the filling state transition of the material at each representative angular position of the die grooves at each amount of die radial feed δ value obtained from FEM simulation. The final deformation state of each modified DTB-II in the analysis well agrees with that in the experiments, and the target screw thread profiles for both cases are obtained for the entire external surface. The thread forming state during rolling in the FEM simulation also progressed as expected. Therefore, both the multiple- and single-thread nuts were fastened easily and smoothly on the thread-rolled DTB-II specimens. However, the equivalent plastic strain distribution, $\bar{\varepsilon}$, of DTB-IIB is very high at the groove bottom and its maximum value reaches approximately 15. In contrast, that of DTB-IIC is very low and its maximum value is 7, less than half of that for DTB-IIB. Hence, in the thread rolling experiments conducted at room temperature, the material temperature immediately after the processing of DTB-IIB increased to 110 °C, whereas that of DTB-IIC increased to only about 70 °C. The reason is that the material filling of the two shallower die grooves located at the center of the 0° position and at the right of the 90° position of DTB-IIB completed in the early deformation stage of $\delta = 0.28$ mm and (surrounded by enclosed space with no room for overflow) then the material was over-rolled, as shown in Fig. 6a. The material near completely filled grooves flows along the same single screw thread to the unfilled deeper grooves, and this material flow in the circumferential direction causes severe shear deformation, leading to material surface peeling and shortening tool life. Many cutting chips appeared in the thread rolling process of DTB-IIB; considerably fewer chips were observed for DTB-IIC. Since the material deformation of DTB-IIC advances in the same manner as that of the normal single-thread bolt, in which the material mainly rises in the radial direction until 70% of δ_{max} (δ0.47 mm), the thread forming state does not depend on angular position. Although material flow in the circumferential direction occurs after the shallow trapezoidal grooves located at the center of the 0° position and at the right of the 90° position of DTB-IIC are filled, as shown in Fig. 6b, its amount is much smaller than that for DTB-IIB, and there is no portion around the groove bottom where is excessively high. These results indicate that the thread rolling formability of DTB-IIC is greatly improved over that of DTB-IIB because of the good thread profile balance in the circumferential direction.

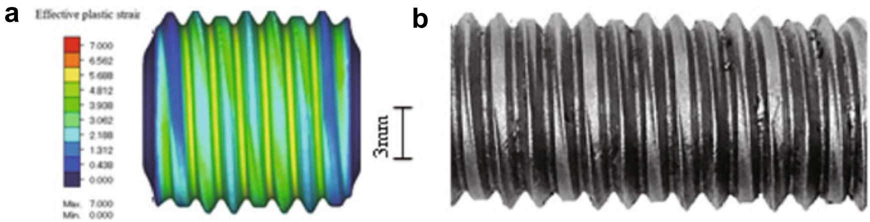

Fig. 5 **a** Equivalent plastic strain distribution of rolled 3-1thread DTB-IIC using FEM. **b** Rolled sample of 3-1thread DTB-IIC used in experiment. (Color figure online)

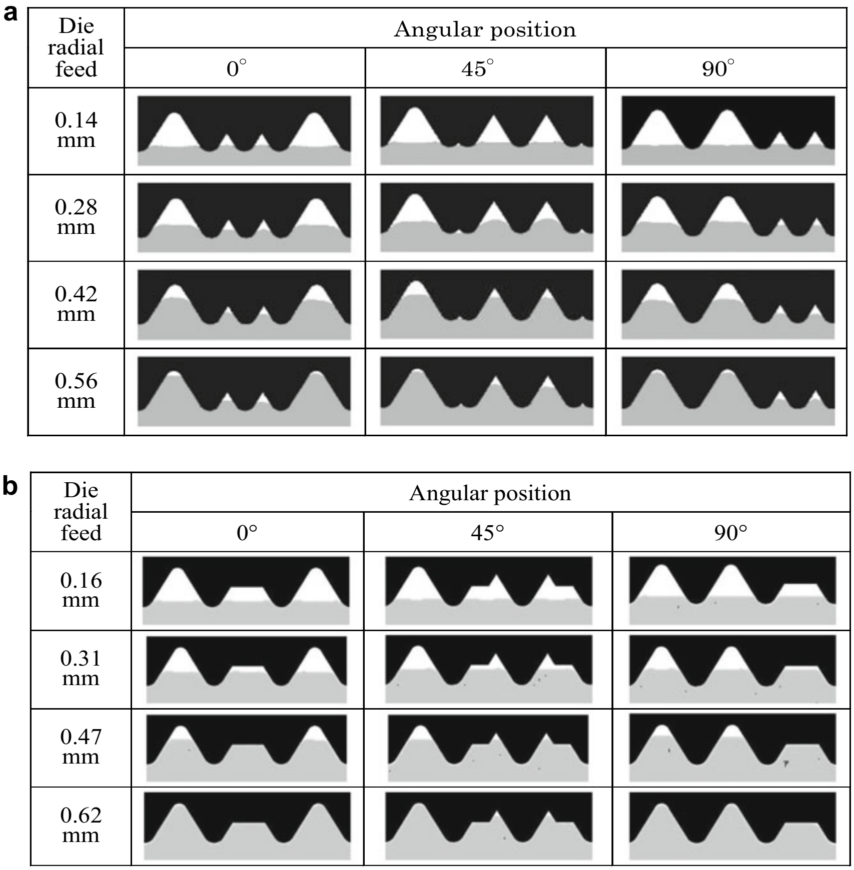

Fig. 6 Comparison of material filling state in various typical sections of die groove using FEM simulation between **a** 3-1thread DTB-IIB and **b** 3-1thread DTB-IIC

3.2 Tensile Strength Tests

The tensile strength tests of M12 rolled 3-1thread DTB-II specimens (denoted DTB-IIs) and a conventional rolled single-thread bolts were conducted using a hydrolic universal material testing machine (UH-300kN made by Shimadzu Corp.) equipped with a special rig with a self-aligning function in the axial direction. A test specimen mounted with double nuts or a single screw nut was placed in the rig and extended at a constant speed of 2 mm/min. The under-head full length of the bolt specimen was 110 mm and the length of the screw portion was 60 mm. The failure mode of all modified DTB-IIs mounted with double nuts was the breaking of the base material and the maximum loads were almost the same as that for the normal single-thread bolt. Here, the non-shear fracture condition of the screw thread was determined by mounting only a single screw nut with different heights, namely normal height (10 mm), 1.25 times normal height (12.5 mm), and 1.5 times normal height (15 mm). Figure 7a–c show the appearance of the fractured DTB-IIB and C with a single-nut structure, and Fig. 7d compares the load-stroke curves obtained from the tensile tests. All these tests were conducted three times under the same conditions; the same results were obtained in each trial. DTB-IIB was damaged by the shear fracture of the screw thread with the 1.25-times-normal-height single nut, and was fractured via necking of the base material with the 1.5-times-normal-height single nut. For DTB-IIC, breaking of base material with the 1.25-times-normal-height single nut and damage by shear fracture with the normal-height-single nut were observed. The maximum load reached approximately 90% (47 kN) in the case of base material breaking. Since the minimum and maximum values of the axial tension of the JIS M12 standard single-thread bolt are 14 and 25 kN [12], respectively, it is possible to use DTB-IIC even with the normal single-nut structure. Accordingly, DTB-IIB and C have remarkably improved tensile strength compared with that of 3thread DTB-II in the previous study [10]. The axial load of DTB-IIC is almost equal to that of the normal single-thread bolt because of the elimination of the small threads at the groove bottom.

3.3 Vibration Loosening Tests

Comparative vibration loosening tests were conducted using the conventional M12 DTB-I and modified M12 3-1thread DTB-IIB and C with a double-nut structure. A Junker test bench (J120T, Vibrationmaster), shown in Fig. 8a, was employed to analyze the self-loosening behavior of secured bolted joints [13]. This apparatus can specify the state in which a bolted joint loses its axial preload when subjected to shear loading by transverse vibration. The transverse displacement and the oscillation frequency were set to 1 mm and 12.5 Hz, respectively, which are the most extreme conditions for this apparatus. The initial axial preload, P_0, of the modified DTB-IIs was set by adjusting only the tightening torque of the outer single nut to be

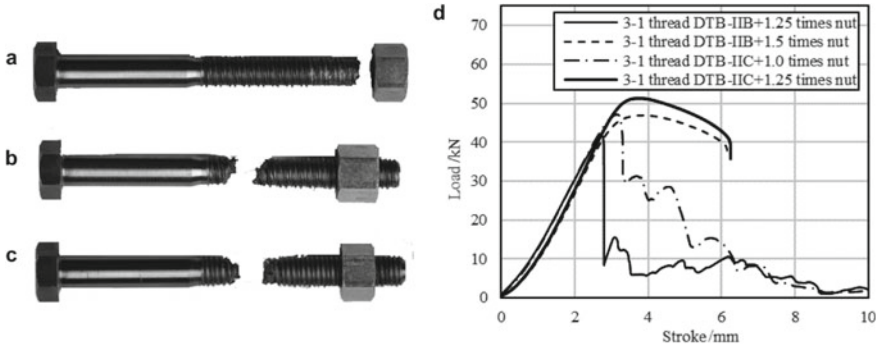

Fig. 7 Tensile strength test results of **a** 3-1thread DTB-IIB with 1.25-times-normal-height sigle nut, **b** 3-1thread DTB-IIB with 1.5-times-normal-height single nut, **c** 3-1thread DTB-IIC with 1.25-times-normal-height single nut. **d** Stroke-load curves obtained from tensile tests

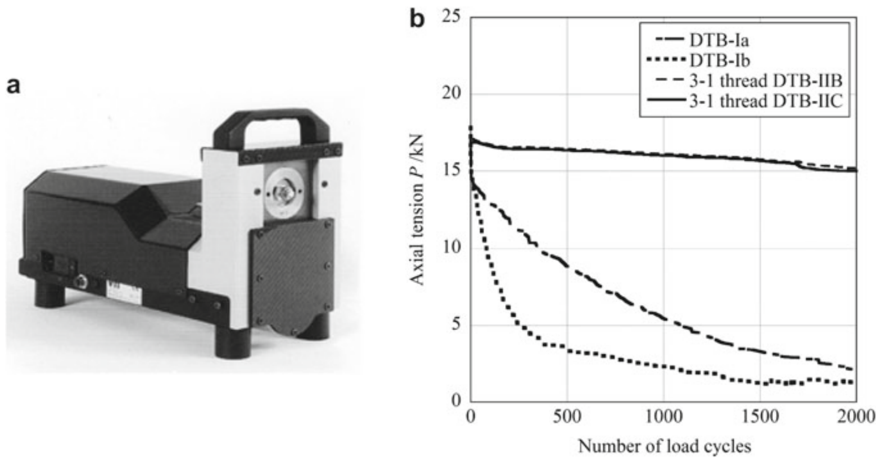

Fig. 8 **a** Junker vibration loosening test bench. **b** Axial tension versus number of load cycles in Junker's vibration loosening tests

fastened later. The proper P_0 for a bolted joint with a nominal size of M12-1.75 is prescribed to be approximately 20 kN in JIS strength class 4.8. However, since the anti-loosening performance of the modified DTB-IIs was so high that the axial force hardly decreased when tightening was conducted with the specific axial load, the bolt head shank exhibited shear fracture during testing. P_0 was thus set to a slightly lower value, within the range of 17–18 kN. A test was considered to have completed when the total number of oscillations exceeded 2000 cycles (about 160 s) or when it became apparent that the bolted joint had loosened. Figure 8b shows the variation in the axial load of the conventional DTB-I and modified DTB-IIs with the number of load cycles in the Junker vibration test. Here, DTB-Ia denotes the case where the inner nut was rotated back according to the regular instruction, and DTB-Ib denotes the case where that procedure was omitted. The final residual rate of the axial load was approximately 15% for DTB-Ia and 10% for DTB-Ib. In contrast, those for the two DTB-IIs were larger than 85%, which is considerably higher than those for DTB-I and exceeds the reference value of 80% given in DIN25201. A detailed comparison of the changes of the axial load indicates that the rates of both DTB-Ia and DTB-Ib suddenly drop by about 4 kN immediately after the starting point; then, that of DTB-Ia continues to decrease with a nearly constant slope, whereas that of DTB-Ib rapidly decreases for about 300 cycles and then decreases very gradually. The rates of both DTB-IIs are almost constant after an initial decrease of about 1 kN. The reason for this significant difference is as follows. (i) The loosening speed ratio between the inner nut and the outer nut of DTB-IIs is 3:1, which is larger than that of DTB-I (2:1). (ii) The outer nut of DTB-IIs with a single coarse screw thread can hold the axial load of a bolted joint more strongly than can DTB-I with a single fine screw thread.

4 Conclusions

1. The rolling formability of the modified 3-1thread DTB-II specimens was considerably improved. Since the material deformation of DTB-IIC advanced in the same manner as that of the normal single thread bolt up to 70% of the total amount of die radial feed, the over-rolled area was greatly decreased around the thread groove portion and the material temperature immediately after the processing was much lower compared with that for DTB-IIB (70 °C vs. 110 °C).
2. The tensile strengths of DTB-IIB mounted with a 1.25-times-normal-height single-thread nut and DTB-IIC mounted with a normal-height single-thread nut reached the range of 14–25 kN prescribed by JIS.
3. It is found that both DTB-IIB and DTB-IIC have outstanding anti-loosening performance, as determined using Junker vibration loosening test. The final residual axial loads were kept at more than 80% after the prescribed 2000 cycles by adjusting only the tightening torque of the outer single nut to be fastened later.

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