Failure of Fastening Screws and Their Preventive Methods

A new method for improvement of the fatigue strength of bolt (the first half), 6th report

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1. Introduction

In the first report, the author has referred that a surprisingly large number of bolts are used in a widely variety of machines and equipment, etc. Therefore, it might be thought that bolts cause, in reality, the largest number of failures among mechanical parts. As far as bolts failures, more than 90% of failure cases would be caused by fatigue and about 80% of failure cases are responsible to the fabricators[1]. In addition, several examples of bolt failures are described by fatigue and their macroscopic fractures are analyzed with simple calculation methods in 2nd report [2]. As environmental failure is limited to high-tensile bolts which are very sensitive to a corrosive environment, the 3rd and 4th reports had introduced environmental failures of bolts which are called "delayed fracture" and "stress corrosion crack"[3][4]. The 5th report explains the factors related to fatigue strength of bolts and refers the conventional methods for fatigue strength improvement of bolts[5].

This report and the next one (7th report) will introduce a new method for remarkable improvement of the fatigue strength of bolts[6]-[9]. Therefore, the author has tried to study the effect of many factors on fatigue strength of bolts and nuts for fundamental approach in the first half as shown in Fig. 6.1.

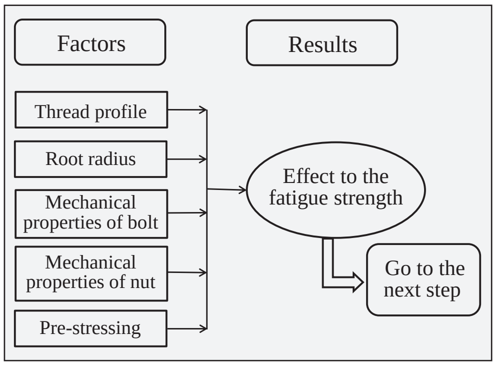


Fig.6.1 Many factors related to fatigue strength

2. Effect of thread profile and other factors on fatigue strength

2.1 Introduction

Normally, the fatigue limit of bolts is 5-6 kgf/mm^2. This fatigue limit is not so high. Since bolts are mostly used under the tightened condition, some part of a variation in the external force is shared by the fastened part. Accordingly, the critical stress for bolts is 15-60 kgf/mm^2, which is equal to or higher than the fatigue limit of welded structures.

First, the effect of thread profile on fatigue characteristics is studied below from the standpoint of improvement of the fatigue strength of bolts[6]-[8].

2.2 Materials used, test specimens and test method

The chemical composition of the materials used for the tests are shown in Table 6.1. The steels used for the nut and bolt are SCM440 and SNCM630. In addition, S20C was used to study the effect of partial damage of the nut on the fatigue strength (see Table 7.1, in 7th report). All specimens except S20C steel were taken from the depth at R= 200mm in radius of the material bar in such a way that the longitudinal direction of the bar coincides with the central axis of each test specimen. All of the specimens, including the threads were finished by turning. The mechanical properties of the steels are shown in **Table 6.2**. Fatigue tests had been conducted on the following items.

Table 6.1 Chemical composition of materials used

Kind of steel	C	Si	Mn	P	S	Ni	Cr	Mo
SCM440 (Ø455)	0.41	0.35	0.73	0.0013	0.020	0.08	1.02	0.21
SNCM630 (Ø470)	0.29	0.25	0.44	0.009	0.006	2.97	2.98	0.59
S20C (Ø40)	0.09	0.01	0.41	0.008	0.005	-	-	-

The numbers in parentheses denote the size of material

Table 6.2 Mechanical properties

Kind of steel	PS [kgf/mm^2]	TS [kgf/mm^2]	E1 [%]	RA [%]	Impact value [kgf·m]	
					$_{V}E$ 20°C	$_{u}E$ 20°C
SCM440	59.4	80.7	21.0	-	2.7	-
SNCM630	91.0	103.0	22.0	61.4	-	10.3
S20C	>25*	>41*	>28*	H_V(10kgf) 203	-	-

* : Specified value PS; proof stress, TS; tensile strength, El; elongation, RA; reduction in area

(a) Effect of type of thread

The effect of triangular thread, trapezoidal one, positive buttress one and negative buttress one were studied. The profiles of these threads are outlined in Fig.6.2. The details of the above screw threads of bolts are listed in Table 6.3. Although the outside diameter of the thread or the root radius may slightly differ among these threads, the root diameter of all of the threads is unified to be φ25mm.

(b) Effect of root radius

Three root radii, r; 0.30, 0.50 and 0.70mm, were selected. The outline and details of thread profile are shown in Fig. 6.3 and Table 6.3, respectively.

(c) Effect of bolt and nut materials

In almost all tests, the bolt and nut made of SCM440 were used. A study was also made with a material with higher strength (SNCM630) for the bolt. Moreover, as a nut is generally stronger than a bolt, a study was also performed with the nut made of the material with lower strength (S20C).

(d) Effect of pre-stressing

As described in the preceding section, this test method is pretty effective but is not adopted widely on site. Accordingly, a brief description is given below. Before a fatigue test, a tensile stress was statically applied to the bolt with a nut in the axial direction. Pre-stress of 43 and 37 kgf/mm^2 were selected for the combination of the bolt and nut made of SNCM630 and for the combination of the bolt made of SNCM630 and the nut made of S20C, respectively. All stresses are the nominal stresses at the root diameter (φ25mm).

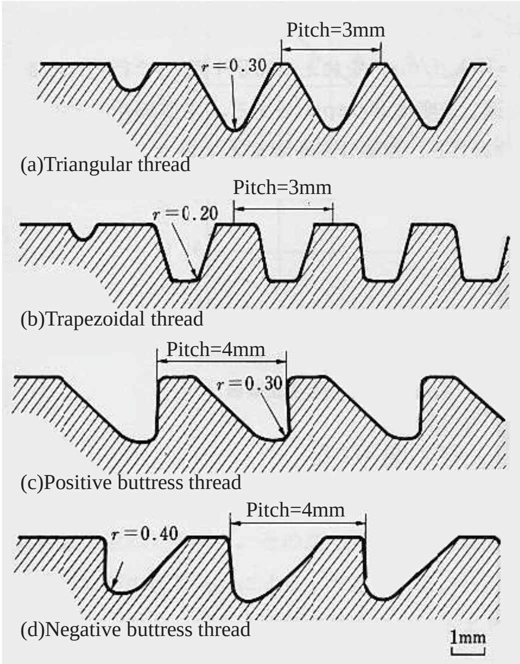
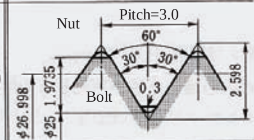
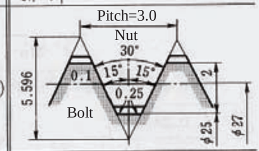
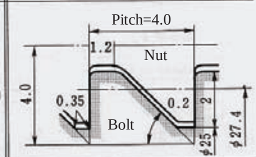
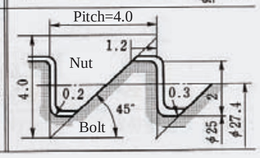


Fig.6.2 Outline of thread profile of various type of thread

Table 6.3 Details of screw thread of bolt (see Fig. 6.2)

Kind of steel	Type of thread	Details of thread profile
Bolt SCM440 Nut SCM440	Triangular thread (ϕ25, r*=0.30)	
	Trapezoidal thread (ϕ25, r*=0.20)	
	Positive buttress thread (ϕ25, r*=0.30)	
	Negative buttress thread (ϕ25, r*=0.40)	

*=measured value

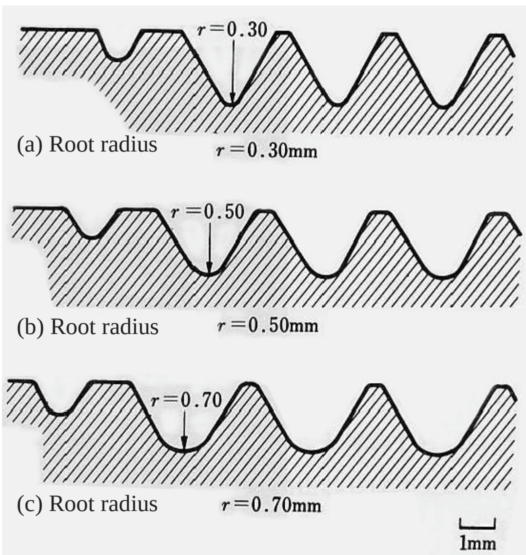
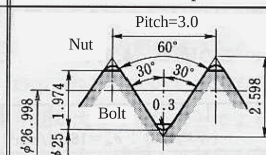
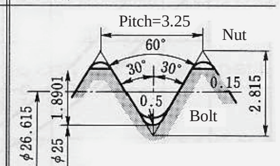
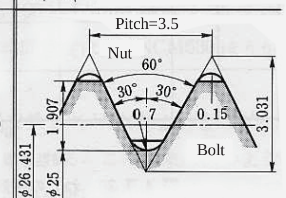
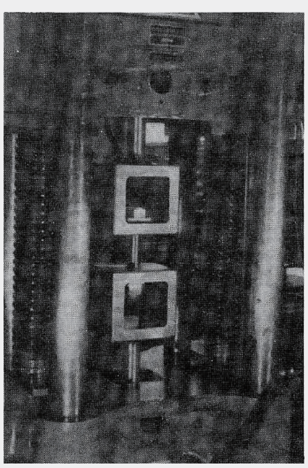


Fig. 6.3 Outline of thread profile with different root radii

Table 6.4 Detail of thread profile (see Fig. 6.3)

Kind of steel	Type of thread	Details of thread profile
Bolt SCM440 Nut SCM440	Triangular thread (ϕ25, r=0.30)	
	Triangular thread (ϕ25, r=0.5)	
	Triangular thread (ϕ25, r=0.7)	



Testing machine: electrical servo controlled fatigue testing machine
Maximum capacity: ±40tf
Type of stress: partial pulsating tensile stress
Mean stress: constant at 18kgf/mm^2
Frequency: 500 cycles/min

Fig. 6.4 Testing condition of bolts

All specimens were subjected to partially tensile pulsating fatigue test with a mean stress σm. For this test, a servo type fatigue tester (±40 tf) was used. The frequency was 500 cycle/min. The S-N curves were obtained for all specimens. The fatigue strengths of the specimens at 2×106 cycles were compared. The testing condition of bolts is shown in Fig. 6.4.

2.3 Results of tests and discussion

The effect of kind of screw on the fatigue characteristic is shown in Fig.6.5. In the case of the triangular thread which is the most widely used, its fatigue strength at 2×106 cycles (hereinafter the fatigue strength is called the fatigue limit unless otherwise specified) is 6 kgf/mm^2. Though it is generally practical to express the fatigue limit in terms of fatigue strength at 107 cycles, the strength at 2×106 cycles may be used in view point of the frequency of the fatigue tester and for practical use. As the specimens are finished by turning, a fatigue strength of 6 kgf/mm^2 is considered almost reasonable compared with the values shown in Table 5.1 of the 5th report. The fatigue limit of a positive buttress thread is nearly equal to this value, but the fatigue strength and fatigue limit of trapezoidal and negative buttress threads are slightly higher. This may be attributed to the relaxation of stress concentration at the root. Setting aside the trapezoidal thread, however, machining of a negative buttress thread is rather difficult. At the present time, this type of thread lacks wide applicability because of this difficulty for machining. In any case, the fatigue characteristic of a thread cannot be improved as expected even if the type of thread changed. If workability is taken into account, the triangular thread has an excellent total balance beyond our expectation.

Figure 6.6 shows the effect of root radius. In this test, the root radius r was limited to 0.30-0.70 mm, and therefore the results of the test may not necessarily applicable to all cases. From Fig. 6.6 only, however, the root radius has little effect on their fatigue strength, although some variations are observed. In all cases, the fatigue limit is 6 kgf/mm^2. The stress concentration at the root decreases with increasing root radius. However, if the root radius is increased, the rigidity of the threads is increased and localized contact with the internal threads is more likely to increase. It is considered that these effects cancel each other, causing little change in the fatigue limit. It may be necessary to conduct further tests, changing the root radius over a very wide range. Anyway, the thread profile should be determined by considering all the factors involved in a comprehensive way.

The effect of bolt material is shown in Fig. 6.7. This figure shows the effect of changing the material of both bolt and nut from SCM440 to SNCM630. The tensile strength is increased by about 25% from 80 to 100 kgf/mm^2 by changing the material. In this case, there is little difference in fatigue limit itself between the two materials. However, the fatigue strength of SNCM630 is lower by about one-fifth in term of the number of cycles. It is widely known that the fatigue strength can be normally improved by increasing the tensile strength of the material. However, the results shown in Fig. 6.7 are the opposite. This effect can be explained as described below. That is, the effect shown in Fig. 6.7 is attributed to two factors. One is that the bolt is a kind of a notched specimen. In ordinary fatigue, the fatigue limit of a plain specimen tends to increase with increasing tensile strength. However, even if the tensile strength is increased with decreasing notch radius, this difference in tensile strength does not have a noticeable effect on the fatigue limit [9]. This is because the notch sensitivity of a notched specimen increases with increasing tensile strength and the fatigue strength of this specimen decreases more than that of the plain specimen.

The other is that the force is transmitted in the bolt through contact between the external threads and the internal ones. If the tensile strength is increased, the contact between the nut and the bolt is apt to become one-sided microscopically, although this contact seems to remain changed macroscopically. In other words, the effect shown in Fig. 6.6 is attributable partly to localized contact. Examples in which the fatigue limit of the bolt is hardly changed even if the tensile strength is increased or in which the fatigue limit is markedly decreased with increasing bolt diameter [10][11] are attributed to the same factor. As bolts are manufactured separately from nuts, the pitch of the bolt differs from that of the nut in the strict sense even if the nominal pitch is the same. Moreover, the bolt receives tension in service but the nut is subjected to compression. Accordingly, the applied contact force between the bolt threads and the nut ones is not relaxed as the material is hard to yield causing localized contact. If the tensile strength of the material is low, however, the material yields easily and the yielded part is plastically deformed, resulting in an increase in contact area. In other words, there may be cases of a reverse effect on the fatigue strength if the tensile strength of the material is increased.

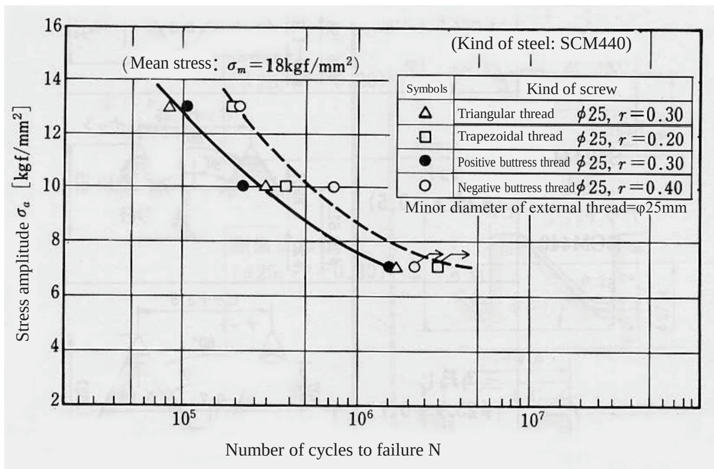


Fig. 6.5 Effect of kind of screw on fatigue strength

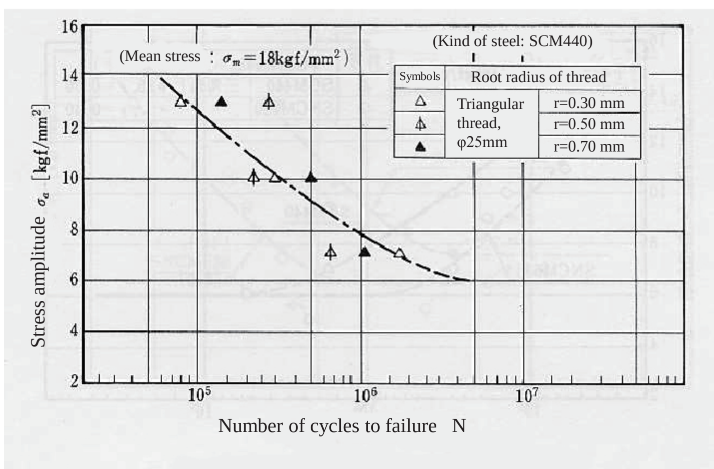


Fig. 6.6 Effect of root radius on fatigue strength

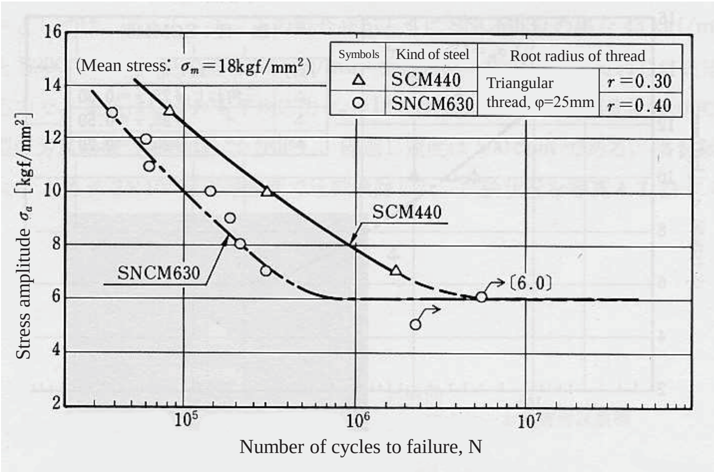


Fig. 6.7 Effect of mechanical properties on fatigue strength

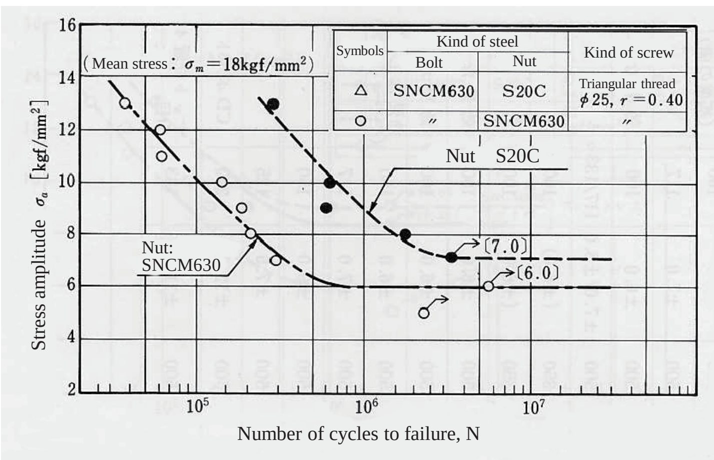


Fig. 6.8 Effect of mechanical properties of nut on fatigue strength

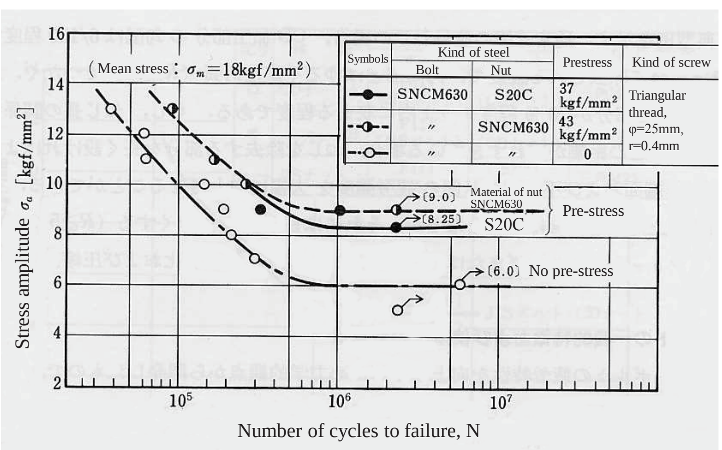


Fig. 6.9 Effect of pre-stress on fatigue strength

Figure 6.8 shows the effect of the composition of a nut on the fatigue characteristic. The fatigue limit for S20C (7 kgf/mm^2) is improved by 17% compared with that for SNCM630 (6 kgf/mm^2). Furthermore, the fatigue strength is increased by about ten times in terms of the number of cycles. The nut has a larger root diameter than the bolt. The bolt is subjected to a tensile force at the time of loading, while the nut receives a compressive force and is hardly fractured. Accordingly, a considerable effect can be expected by making the nut of a material which is softer than the bolt material.

We often say that 'this easily fits or does not fit easily'. When a force is transmitted by the contact between more than two parts, such as in the combination of a nut and bolt, the stress can be reduced if the force is received by a larger area. Normally, it is said that the microscopic contact area is less than 10% of the macroscopic contact one. If the nut or bolt or both are made of a softer material, the microscopic contact stress can be reduced. Since fracture is more likely to occur in the bolt because of tightening, better results will be obtained by using a soft material for the nut. According to the author's experience, it is desirable to set the ratio of tensile strength of the bolt to that of the nut within the range 1:0.4-0.8. Some researchers are of the opinion that the fatigue characteristic can be greatly improved by using a cast iron which has a lower elastic coefficient than a carbon steel [(10)]. As described later, the use of a cast iron aims to equalize the load to be shared by the threads by decreasing the internal stress applied to the bolt for the external force.

Figure 6.9 shows the effect of pre-stressing on the fatigue characteristic. The pre-stress of 37 kgf/mm^2 was applied in the case of the combination of a bolt made of SNCM630 and a nut made of S20C. When both the nut and bolt are made of SNCM630, the pre-stress of 43 kgf/mm^2 was applied. In other words, the pre-stress to the former combination was lower by 16% than that to the latter combination. In both combinations, the fatigue strength was increased by pre-stressing. The ratios of increase in fatigue strength were 38% and 50%, respectively. These increases are attributable to such factors as the improvement in the strength of bolt threads by cold working and the resultant effect of compressive residual stress, equal load sharing among the bolt threads, and the relaxation of microscopic localized contact between the bolt threads and the nut ones. In the case of the nut made of S20C shown in Fig. 6.8, the nut is more likely to yield than the bolt. The reason is that the yielding at the bolt thread root was not sufficient compared with the case where the nut was made of SNCM630.

There are still several items requiring further study, including determination of the limit of improvement of fatigue strength by changing the pre-stress over a wide range, and selection of an optimum nut material in the case when pre-stress is applied. In any case, the fatigue limit of the bolt is improved by 50% by pre-stressing. Yunker pointed out that the fatigue strength was increased by tightening the bolt under a load higher than the yield point (11). Maruyama explained the reason why the fatigue strength was improved by fastening in the plastic range [(12)]. Although the test method and effect differ in detail, both researchers are based on the same idea. The results are summarized later (see 7th report).

3. General evaluations

As shown in Figs. 6.5-6.9, most of the results about fatigue strength of bolts are not so remarkable as expected. But, it will be distinguished that the fatigue limit of the bolt was improved by 50% by pre-stressing. The increase is attributable to such factors as the improvement in the strength of bolt threads by cold working and the resultant effect of compressive residual stress, equal load sharing among the bolt threads and the relaxation of microscopic localized contact between the bolt threads and nut ones.

As bolts are usually used under the fastened condition, the bolts are loaded one part of the total external force (the other external force is applied to the fastened part). Therefore, the above improvement can be said remarkable effect when it is converted into the external load. The defect of the pre-stressing is not suitable for mass production because the combination between bolt and nut should be applied tensile force to their axis over plastic deformation. A small amount of the combination of bolt and nut can be practically applicable for the pre-stressing.

According to the above results, the author has considered that the idea to improve the fatigue strength more remarkably and that method should satisfy mass production process in the view point of industry. This method will be referred in the next report (7th report).

4. Conclusion

As described before, this report and the next one will introduce a new method for remarkable improvement of the fatigue strength of bolt. Therefore, the author tries to evaluate the many factors, e.g., thread profile, mechanical properties of bolt or nut, pre-stressing, etc. related to fatigue strength, individually as a fundamental approach.

The main results described above in this report are summarized below:

(1) Effect of type of thread; the fatigue limits of the four kinds of bolts, triangular thread, positive buttress thread, trapezoidal thread and negative buttress thread are nearly the same and to be 6kgf/mm^2, though the fatigue strength and fatigue limit of trapezoidal and negative buttress threads are slightly higher. Setting aside the trapezoidal thread, however, machining of negative buttress thread is rather difficult.

(2) Effect of root radius; the root radius has little effect on fatigue strength in the range of 0.3-0.70mm and the fatigue limit is all 6kgf/mm^2.

(3) Effect of tensile strength of bolt materials; when the material of both bolt and nut is changed from SCM440 to SNCM630, the fatigue strength of SNCM630 becomes lower by about one-fifth in term of the number of cycles. This is due to localized contact between bolt and nut threads (see Table 7.2, last half report).

(4) Effect of tensile strength of nut materials; the fatigue limit for S20C is improved by 17% compared with that for SNCM630. Furthermore, the fatigue strength is increased by about ten times in terms of the number of cycles. This result is caused by the same factor as shown in the above.

(5) Effect of pre-stressing; the fatigue strength was increased by pre-stressing and the ratios of increase in fatigue strength were 38% and 50%, respectively. These increases are attributable to cold working, compressive residual stress, equal load sharing and the relaxation of microscopic localized contact between both threads.

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