“Fastener Troubles, Causes & Solutions” Series

Failure of Propeller Shaft Couplings — Reamer Bolts Transmitting High Torque

by Toshimichi Fukuoka

In the U.S. and Europe, jointed parts fastened with threads are called “bolted joints” as a whole. Various external forces exert on bolted joints, and they cause the problems of “fatigue failure of bolted joints” and “thread loosening”. Among the loads exerting on bolted joints, when shear loads are applied perpendicularly to a bolt shank, slip could occur on the plate interface, nut bearing surface, and the bolt head bearing surface. The slip induced by shear loads is the primary cause of fatigue failure and thread loosening. Typical mechanical elements with high shear loads being exerted on bolts in this way are shaft couplings. Bolts that clamp shaft couplings are subjected to high shear loads due to the torque transmitted from the shafts. In such cases, the use of common bolts may cause slips on the interface of the coupling. To cope with the problem, a special bolt called “reamer bolt”, whose shank diameter is equal to the bolt hole diameter, is frequently used. Despite the extensive use of reamer bolts, their mechanical properties are barely known to us. Hence in this article, I will explain the characteristics of reamer bolts as a threaded component, the fastening methods, and the mechanical behavior when subjected to external loads.

Figure 1

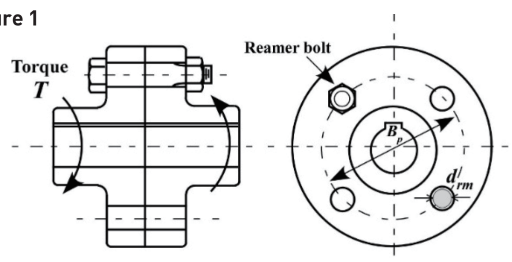
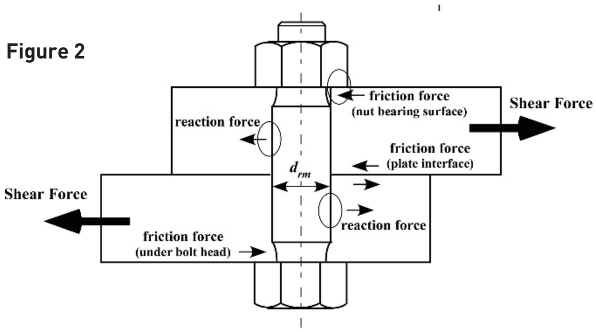


Figure 2



What is a Reamer Bolt?

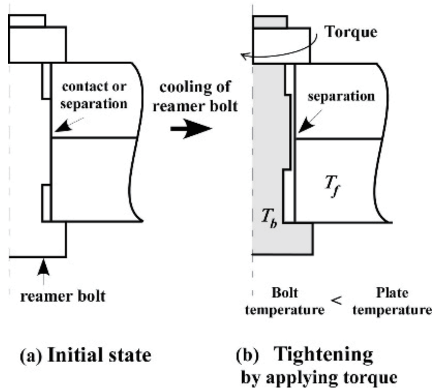
Figure 1 shows an example of the Japanese Industrial Standard for a shaft coupling. In terms of this coupling, the size is small and 4 reamer bolts are used to fasten the coupling. As the size increases, the number of bolts also increases. Shaft couplings are used to transmit torque between the two shafts fixed respectively to each couplings. In that case, very high shear loads exert on the interfaces between the two couplings, shown in Figure 1. In addition, the counteracting friction force is equal to the product of the sum of the axial bolt force and the coefficient of friction on the interface. If the shear force caused by the torque is larger than the friction force, slips occur on the interface of the coupling, which causes bolt loosening and fatigue failure. A countermeasure against those problems is to use reamer bolts. Reamer bolts, as shown in Figure 2, have larger shank diameters than common bolts. It is a fundamental practice that the diameter d_{rm} is equal to the hole diameter of the bolt. In actual practice, however, the diameter d_{rm} is mostly machined to be as much as a few mm larger than the bolt hole diameter. That is because when we apply axial force to the bolt, the diameter d_{rm} slightly shrinks in the diameter direction. In case of M20 bolt for example, if we fasten it with axial stress of 200MPa, its diameter shrinks by amount of around 6mm. The reamer bolt in Figure 1, used for a shaft coupling, transmits the torque by contacting its shank with the bolt hole. In Figure 2, it is shown how the shear force caused by the torque exerts on the shank of the reamer bolt and the contact surface of the coupling. As an example, reamer bolts are commonly used for shaft couplings of propeller-shaft systems of ships in order to transmit a very high torque.

Fastening of Reamer Bolts

Since the shank diameter of a reamer bolt is slightly larger than the bolt hole diameter, a special method is used to fasten it. Generally, dry ice or liquid nitrogen is used to cool down and shrink the bolt, and in that state a reamer bolt is inserted into the bolt hole and the torque is applied to fasten it. To make it easier to insert a reamer bolt, formerly we used to heat up the surrounding portion of the bolt hole to expand the hole diameter. However, recently the cooling method has been used widely in order not to change the material properties. Figure 3 shows the fastening process of a reamer bolt. Figure 3(a) shows the pre-fastening initial state. In actual practice, however, the reamer bolt cannot be inserted due to the aforementioned reason. Therefore, the reamer bolt is cooled down and inserted into the bolt hole, and then the torque is applied (Figure 3(b)). At this point the operation is completed, but a critical problem pertaining to fastening precision still remains. It is the fact that when the fastening is completed, the reamer bolt still remains in a low temperature state. The degree of the temperature would change significantly depending on whether dry ice or liquid nitrogen is used. In addition, the degree also changes depending on the required time from cooling down of the bolt to the completion of fastening. In other words, the problem pertaining to fastening precision is that the bolt elongates and the axial force of the bolt decreases because the bolt temperature returns to the room temperature after the operation is completed. Supposing that the difference between the average temperature of the reamer bolt and room temperature at the completion of the tightening operation is ΔT, we can calculate ΔF_b using the following expression.

$$\alpha_b \Delta T L_f = \Delta F_b \left(\frac{1}{k_{th}} + \frac{1}{k_s} + \frac{1}{k_{cyl}} + \frac{1}{k_{hd}} + \frac{1}{k_f} \right)$$

Figure 3



The above expression is the same as the one for the fastening process of Thermal Expansion Method explained in my last article (the 5th article of the Series). Here I will omit the detailed explanation. α_b is the coefficient of linear expansion of the bolt material. L_f is the grip length. The 5 terms within the parentheses are the spring constants for each part of the bolted joint. Figure 4 shows the relationship between "the amount of decrease in bolt axial stress per 1℃ rise of temperature" derived from the above expression and the "grip length". The horizontal axis is the ratio of the grip length to nominal diameter d. According to **Figure 4**, we know that the amount of decrease in bolt axial stress per 1℃ rise of temperature increases with grip length and ranges from 1 to 2 MPa regardless of bolt size. In the experiments conducted in my lab using dry ice of minus 80℃, the average temperature of the reamer bolt was around minus 30-40℃ when the fastening was completed. Assuming that the average temperature is minus 30℃ and the room temperature is 20℃, the temperature increase of the reamer bolt becomes 50℃, and so the axial stress would decrease as much as 50 to 100MPa. Since the axial stress of a reamer bolt is usually high, it is considered that this degree of axial stress reduction would rarely be the critical reason for causing troubles. However, we should note that axial stress will decrease significantly when we complete the operation quickly using liquid nitrogen of minus 196℃ for cooling.

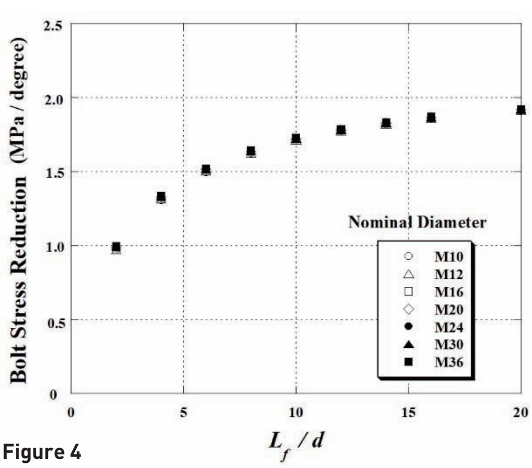
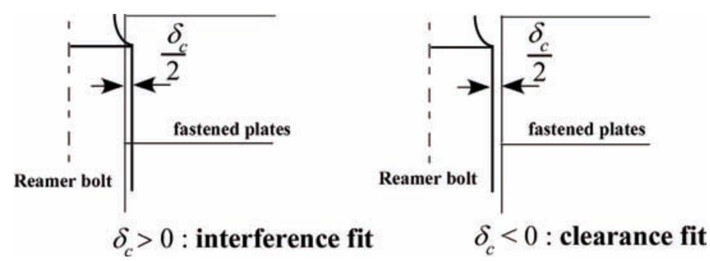


Figure 4

Behavior of Reamer Bolt Subjected to Shear Load

Figure 2 in the second paragraph shows the equilibrium of forces when the joint using reamer bolts is subjected to shear loads. The shank of the bolt is closely in contact with the bolt hole. In contrast, in case of common bolts, there is a gap between the shank and the bolt hole. Consequently, the shear force applied to the joint is sustained by the friction forces on the interface between the fastened objects, the bearing surface of nut, and the bearing surface of bolt head. If the shear force is larger than the friction force, slips occur on the interface, which may lead to the loosening of the bolt and the fatigue failure of the bolted joint. For preventing such slips, it is sometimes observed that people working in the architecture fields intentionally increase the coefficient of friction on the surface of the fastened objects. On the other hand, if we use the reamer bolt shown in **Figure 2**, a significant proportion of the shear force would be supported by the bolt shank. In other words, the shear force exerting on the reamer bolt is supported by the forces perpendicular to the bolt shank and the friction force on the interface. The proportion between the two forces greatly changes depending on the fit between the reamer bolt and the bolt hole, coefficients of friction on the contact surfaces, and the magnitude of the axial bolt stress. **Figure 5** shows the conditions called "interference fit" and "clearance fit". In the former condition, the diameter of the bolt shank is larger than that of the bolt hole; in the latter condition, there exists a small gap. Reamer bolts used for couplings of propeller-shaft systems of ships are targeted for an interference fit ranging between a few mm to 10mm. It is reported that the fit shows a scatter between at most -20mm to +20mm in actual measurements. In addition, to evaluate the aforementioned "proportions of the shear force supported by the force perpendicular to the bolt shank and the friction force", sophisticated non-linear analyses are required.

Figure 5



Conclusion

This article explained the basic characteristics of a "reamer bolt", a special bolt widely used for the joints on which large shear loads exert. Shear forces exerting on the joint, which is clamped with a reamer bolt, are supported not only by the force perpendicular to the bolt shank, but also by the friction force on the interface in the same manner as common bolts. In the next article, the aforementioned mechanical characteristics of reamer bolts will be explained, based on the results of finite element analysis. Furthermore, it will also explain the fatigue failure of reamer bolts which is considered the most important issue caused by the repetition of the shear load.

Reference:

1. Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp. 290-304, Corona Publishing Co., Ltd. (2015)

2. Fukuoka, T. and Nomura M., "Evaluation of Tightening Process of Reamer Bolts by Cooled Fitting," ASME PVP 2011 (Baltimore), Paper No.57121 (CD-ROM).