The significance of friction

According to the VDE/VDE 2230 guideline, bolted joints are correctly dimensioned when the minimum preload is sufficient to prevent joint separation and maintain friction contact in the presence of external forces. However, bolted joints sometimes become loose even though they are dimensioned to meet this requirement.

The relationship between friction and the forces inside the bolt plays a major role in this. One-third of the tightening torque is necessary to overcome thread friction, and roughly half of the torque is needed to overcome friction under the bolt head. This means that the higher the friction, the lower the preload. You might therefore think that friction is bad or undesirable, but that is not the case. In fact, the main underlying cause of bolt loosening is the preload, which is what is supposed to hold the bolted joint together. To understand this, you can regard a bolt as a sort of spring that is stretched during assembly and wants to contract due to the resulting force. If the friction in the threads and under the bolt head is high enough, this force is not enough to cause spontaneous loosening of the bolt, which means coming loose without external aid.
However, if the friction is reduced below a certain point, the bolt can loosen by itself. The balance of forces is shown in DIN 25201 Part 4.

This means that the injudicious application of lubricants can reduce the friction that secures bolts and lead to spontaneous loosening. The friction coefficients under the bolt head and in the threads can be measured separately with laboratory systems. Since bolt head friction usually accounts for about half of the torque, it is the most important factor for potential spontaneous loosening.

Temperature dependence of friction coefficients

Even if the friction coefficients of bolts measured under laboratory conditions are within the specified tolerance, this does not mean that they will always be within tolerance under actual load conditions. Particularly in the automotive industry, people have discovered that there are chemical additives in bolt coatings that can change the friction characteristics of bolts at temperatures around 150 °C and cause spontaneous loosening.

There are various ways to test the high-temperature loosening characteristics of bolts. One way is to screw the bolt into a test body and heat it to 150 °C, and then measure the loosening torque.

Thread friction torque (without gradient portion):

\[ M_{GR} = F_T \cdot \frac{d_2}{2} \cdot \frac{v_G}{\cos \alpha} \]

Internal loosening torque (gradient portion):

\[ M_{GST} = F_T \cdot \frac{p}{2\pi} \]

Head friction torque:

\[ M_K = F_T \cdot \frac{D_{hm}}{2} \cdot v_K \]

Tightening torque:

\[ M_A = M_{GR} + M_{GST} + M_K \]

Spontaneous loosening:

\[ M_{GST} \geq M_{GR} + M_K \]

The theory behind spontaneous loosening.

Source: DIN 25201-4:2010-03
Measuring the loosening torque is not straightforward because various torque peaks occur during loosening, so it is necessary to determine the torque on the bolt at the transition between static and dynamic friction.

Then the ratio between the tightening torque and the loosening torque can be calculated. If the loosening torque is 30 percent of the tightening torque or less, it can be assumed that the friction coefficient has dropped below the critical value of 0.06 and there is a risk that the bolt will loosen spontaneously. For other geometric conditions or friction coefficients during assembly, the friction coefficient can be calculated.

A disadvantage of this approach is that the result depends on a number of estimates and assumptions. For instance, the friction coefficient is not measured during assembly, but instead determined in a prior test. The estimated 5 percent loss in preload is based on experience and is not documented by measurements. These issues can be avoided by using a more complex measuring method that can capture all the relevant quantities.

To do this, the bolt is mounted in a special preload transducer with high stability over a large temperature range. Using this transducer, the friction coefficients under the bolt head and in the threads can be measured separately during assembly. Any loss of preload during heating is recorded and documented. Then the bolt is loosened and the loosening torque is measured.

testXpert® automatically calculates the torque MLTh at the transition to dynamic friction.
Investigating changes in friction characteristics in a heat chamber.

**Relative motion of assembled parts**

Bolted joints in which the assembled parts can move relative to each other are a special case. Motion can occur for various reasons:

1. The friction coefficient between the assembled parts is lower than assumed by the designer.
2. The bolt is so long that motion under the bolt head is possible due to elastic motion of the parts, even though there is no actual transverse motion between the parts.
3. Differences between the thermal expansion coefficients of different materials present in an assembly. This causes transverse motion between the materials every time the temperature changes.

There are two options for securing bolts subject to transverse motion: increase the friction under the bolt head, or increase the thread friction. Bolt head friction is usually increased by using radial ribs under the bolt head, while thread friction is increased by using thread locking compounds.

The effectiveness of bolt securing methods is tested on a vibration test stand. A sensor that can separately measure the thread friction is used to determine the loosening torque at the point when the bolt comes loose.

**Settlement of bolted joints**

Along with purely elastic deformation, local plastic deformation occurs in bolted joints during and after assembly, even with stresses below the yield limit, and can lead to loosening of the joint. Plastic leveling of surface roughness under the bolt head is called settlement. The magnitude of settlement depends on the surface roughness of the bolted materials and the number of joint layers.

\[
F_V = \frac{M_A}{(0,159 \cdot p + \mu_{ges,RT} \cdot (0,577 \cdot d_2 + 0,5 \cdot D_{km}))}
\]

\[
\mu_{ges,Lösen,150°C} = \frac{M_{LG}}{0,95 \cdot F_V} + \frac{0,159 \cdot p}{0,577 \cdot d_2 + 0,5 \cdot D_{km}}
\]

*Calculating the friction coefficient for high-temperature loosening.*
Determination of thread torque, torsion moment and internal loosening torque in a vibration test.

For example, if a grade 10.9 M10 bolt with a clamping length of 50 mm is assembled with a tightening torque of 40 kN, it stretches approximately 160 µm. The previously mentioned settlement is approximately 10 µm, resulting in a preload loss of about 2.5 kN, which is certainly acceptable in this situation.

If a grade 10.9 M10 bolt with a clamping length of just 5 mm is assembled with a tightening torque of 40 kN, it stretches only 16 µm. Assuming a settlement of about 10 µm in this scenario as well, the loss of preload is approximately 25 kN. This means that most of the preload has been lost due to settlement.

### Creep of bolted joints

Creep occurs over time when stresses exceed the yield limit of the material, and it causes a loss of preload. This effect is mainly seen when elastic materials are under stress in a bolted joint. After assembly, any material in the bolted joint whose yield limit is exceeded is gradually pressed out of the joint by the high preload of the bolt. This yielding of the bolted joint causes a loss of preload, which can ultimately lead to bolt loosening.

Effects such as settlement and creep must be measured on the actual part. It is often difficult to fit a suitable sensor in the bolted joint to measure the preload. For this reason, it is advisable to use an ultrasonic sensor to measure the preload of the bolt. The bolt must be specifically prepared for this test by gluing an ultrasonic sensor to the bolt head. Sensors for measuring torque, rotation angle and preload by contact with the ultrasonic sensor are available, allowing the full measurement process to be performed with a lab system.

Using an ultrasonic sensor to measure preload and preload loss due to settlement or creep after assembly.
A procedure for performing machine capability tests (MCTs) is described in VDI/VDE Guideline 2645 Part 2. This guideline says that industrial manufacturing processes are affected by various parameters. These parameters are usually called “5M” in German, which stands for man, machine, method, material, and ambient conditions.

Machine capability tests measure the stability and reproducibility of machines as process parameters. This allows conclusions to be drawn about possible process faults due to machines, which in turn can be used for objective comparison of the quality of different machines.

MCTs can be used to ensure that only suitable fastening tools are employed.

The guideline describes a significant change in the short-term monitoring of fastening tools. In the past it was common practice to take a small set of random samples, for example five measurements, and check whether or not the measured values were within tolerance. A drawback of this approach is that tools that are no longer performing properly are not detected until out-of-tolerance measurements are found. Depending on the importance of the bolted joint, this may require retesting or rework of all parts made since the last sampling point that yielded results within tolerance. By contrast, the method described in Part 2 of VDI/VDE Guideline 2645 checks the statistical capability of tools. This allows tools that are no longer able to work within the process limits to be identified even when no values outside the process limits have been measured.

The guideline distinguishes between tool-related MCTs and joint-related MCTs. For fastener-related MCTs, there are now mobile test systems available with controlled bolted joint simulators that can accurately simulate the characteristics of actual bolted joints. These mobile test systems can be used to check pneumatic, electrical and impact fastening tools in place on the assembly line.

The cut-out characteristics of fastening tools depend on the hardness of the bolted joint. The joint hardness determines how far the bolt head turns between snug-down and the final tightening torque. For example, a short bolt used to fasten a piece of sheet metal can reach its final torque level after about 30 degrees of rotation. This is called a hard bolted joint. The opposite situation is present in bolted joints with long bolts or elastic materials. In such joints the bolt may have to be turned by a full rotation – 360 degrees – from the snug-down point to reach its final tightening torque. That is called a soft bolted joint.

Since the joint hardness can affect the cut-out characteristics of fastening tools, it is important for the simulator to have the same characteristics as the actual bolted joint.
Periodic monitoring of fastening tools basically takes place locally on the assembly line. The settings of the fastening tool should not be changed during testing. The measuring session is conducted and documented with the actual settings.

Local joint-related MCTs are oriented to process specifications. The total scope of random samples is 50 measurements, and the tolerances recommended by the guideline are $\geq 2.0$ process tolerance for the CM value and $\geq 1.67$ process tolerance for the CMK value. The guideline also allows the test scope to be reduced to 25 measurements, but different CM and CMK values are required in that case.

With hand-held fastening tools, on-site testing with the simulators is straightforward because the tool can easily be tested on the simulators installed in the test stand. The situation is different with built-in fastening tools, which are permanently mounted in a fixture and cannot be removed from the fixture and mounted on the simulator for machine capability verification without a lot of effort. The "Body Chassis Marriage" in the automotive industry poses a special challenge. Where the chassis with the suspension components and the body are joined together, a large number of fastening tools mounted in the fixture have to assemble a large number of bolts at the same time so that the marriage can be completed in a single operation. These fastening tools are permanently mounted in the fixture, and some of them are oriented at an angle to reach the right bolts.

To carry out machine capability testing on these fastening tools, special types of bolted joint simulators are used that allow a small simulator with integrated torque and rotation angle instrumentation to be mounted directly on the tool to be tested.

The simulator is held in the right position for the fastening tool by a manipulator. A swivel mechanism allows it to be used with fastening tools mounted at any desired angle.

A mobile test stand with a manipulator is therefore able to perform machine capability tests in accordance with VDI/VDE Guideline 2645 Part 2 on built-in fastening tools without requiring them to be removed from their fixture.
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