PDHonline Course S247 (2 PDH)

Fastener Facts

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2020

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Course Content

Although selection of bolts, nuts and washers may appear as a difficult task, in reality it is quite simple as long as factors such as operating temperature, service environment, corrosion, vibration, initial clamping load (torque) and cyclic loading (fatigue) are carefully considered. If the main function for the fastener is strength, then steel is probably the most appropriate type to use. If the service environment is corrosive, then either steel with a protective coating or stainless steel or a nonferrous alloy should be considered. If magnetic permeability is important then an austenitic stainless steel, aluminum or copper alloy should be used. If high electrical conductivity is needed, aluminum or copper fasteners can be used. For weight saving situations aluminum is the main solution. If high strength is coupled with weight consideration, as in aerospace applications, then titanium may have to be selected. For high and low temperature service stainless steels or superalloys (with high alloying additions of nickel, molybdenum, cobalt, vanadium etc.) should be utilized.

Fastener Materials

Bolts can be made from many different materials but most are carbon, alloy or stainless steel. Titanium and nickel alloy bolts are also used in aerospace applications.

Carbon steel is the most common fastener material. Steels are usually zinc plated (galvanized) to resist corrosion. Typically the tensile strength is around 60,000 psi (pounds/square inch) for low carbon steels. Medium carbon, heat treated fasteners can achieve 120,000 psi and low-alloy steels 150,000 psi. Some higher alloy steels can reach much higher strength levels (up to 300,000 psi) through heat treatment although in most engineering applications (other than aerospace) there is seldom a need to consider any fastener with tensile strengths over 180,000 psi. With steels the poor corrosion resistance necessitates some type of coating in most applications. Cadmium, although being phased out in recent years due to environmental concerns, provides the best corrosion protection. There is also a family of steels that provide relatively good atmospheric corrosion resistance without any coatings. These are known as weathering steels and are widely used in exposed structures such as bridges, buildings and transmission towers. These low alloy steels have significant copper content, which helps build a stable protective oxide surface film when exposed to the atmosphere.

Stainless steel (corrosion resistant-CRES) bolts may come in various types ranging in ultimate strength of 70-220,000 psi. Three basic types of stainless steels (austenitic, ferritic and martensitic) have distinctly different properties. Austenitic (e.g. 303, 304, 316, 321) are non heat-treatable but their properties can be improved through cold working and strain hardening techniques. In general, the solution-annealed versions possess tensile strengths in the 75,000 psi range, cold worked ones may reach 90,000 psi and strain hardened ones my go over 100,000 psi dependent on their size. The ferritic grades, such as 430, do not respond to heat treatment and have tensile strengths of about 70,000 psi. Martensitic grades (i.e. 410, 416 and 431) are heat treatable and can reach 180,000 psi. Major advantage of stainless steel fastener use is that they usually require no additional coating for corrosion protection and have a much wider service temperature range.

In the nonferrous arena, aluminum is the most common fastener material. Aluminum alloys have reasonable strength, a high strength-to-weight ratio, good corrosion resistance in most environments, excellent thermal and electrical conductivity, and perform well at low temperatures. Tensile strength may range anywhere from 13,000 psi (with pure aluminum) to above 60,000 psi with the 2XXX or 7XXX series alloys (e.g. 2024 or 7075).

None of the copper alloys (brasses and bronzes) respond to heat treatment and therefore the strength increase can only be achieved through cold working. However, since many copper alloys, following forming, must be stress relieved to eliminate embrittlement, fastener strengths usually are consistent with base metal levels. Typical strength levels range from 50,000 psi in certain brass alloys to around 100,000 psi for some aluminum bronzes.

Nickel base alloy have excellent strength properties combined with their superior corrosion resistance, toughness, better performance at high and low temperature extremes, which gives them a serious advantage over other alloys. However, their high cost can be a limiting factor. The most commonly used ones among this alloy group is the nickel-copper group (e.g. Monel) with a tensile strength of 80,000 psi and the heat treatable nickel-copper-aluminum, which can achieve close to 130,000 psi tensile strength.

Titanium, because of its superior strength-to-weight ratio, is very popular in aerospace, missile and some chemical processing plant applications where the high cost is justified. Bolts made from Ti-4Mn-4Al and Ti-6Al-4V have tensile strengths of 150,000 psi and other titanium alloys that can reach close to 200,000 psi are available.

Plastic fasteners, which are widely used in electronic and automotive applications, are the lowest strength materials with the widely used nylon fastener having a tensile strength of around 10,000 psi.

Some limitations that need to be kept in mind during fastener selection are:

The plating material is usually the factor defining the maximum service temperature

Carbon and alloy steel bolts become brittle at low temperatures (i.e. below 30 or 40 °F)

Hydrogen embrittlement becomes a problem with high strength steel bolts especially if they are plated

Heat treatable (400 series) stainless steel bolts have reduced corrosion resistance

Coupling of dissimilar metals can lead to galvanic corrosion.

Platings and Coatings

Service environment is a significant consideration when selecting fasteners. Corrosion prevention, whether from atmospheric, galvanic, high temperature oxidation or stress corrosion attack is key to avoiding premature failures. Steel fasteners with some type of plating or coating function well in most atmospheric environments. Generally, the thicker the coating or plating, the more effective the protection.

There are however, certain mechanisms that come into play with coating higher strength fasteners. Most plating processes are electrolytic and generate hydrogen. Additionally, the acid cleaning processes that are performed to prepare the surfaces to be plated are sources for hydrogen pick up by the materials. This causes hydrogen embrittlement. Therefore, for high strength fasteners, most plating processes require a baking treatment after the plating to diffuse the hydrogen out of the material. For example cadmium-plated fasteners must be baked at 375°F for 23 hours, within 2 hours of plating. Low strength materials (i.e. typically less than 32 HRC) are not susceptible to hydrogen embrittlement and do not require baking.

Cadmium is extremely toxic and while it has been established that plated fasteners are not a high-risk hazard, they cannot be used in contact with food or beverages. Its environmental threat relates primarily to the plating process and subsequent handling of plating effluents. Alternative coatings are being developed to replace cadmium, however its superior corrosion protection has not yet been matched with any of the replacement coatings. Besides its high resistance to corrosion, cadmium has lubricity, which lowers the friction coefficients and narrows the range of torque-tension relationships. The service temperature limit for cadmium-plated fasteners is 450°F since cadmium melts at 600°F.

Zinc is also a very common plating type. The hot-dip method is commercially known as galvanizing. Zinc can also be electrodeposited. Since zinc is a sacrificial material, it will continue to provide protection in areas where the plating may be scratched off or removed. Zinc may also be applied cold as a zinc-rich spray paint. Useful service life expectancies of zinc plated fasteners in various environments are: Zinc plated with chromate treatment having 0.15 mils (0.00015 in.) plating thickness may last up to 20 years indoors, about 4 years in rural atmosphere, 2 years in coastal locations and less than 1 year in heavily polluted industrial areas. Hot-dip galvanized fastener with an average thickness (coating weight) of 1.25 oz/sq. ft will last over 40 years in rural atmosphere, 25-30 years in coastal and about 5 years in heavily polluted industrial areas (1 oz/sq. ft = 1.7 mils). Although zinc melts at 785°F, its useful service temperature is 250°F since its corrosion inhibiting qualities degrade above 140°F. Zinc plated fasteners require more tightening torque to develop equivalent preloads in fasteners. Also, zinc without some supplementary protection develops a dull white corrosion product (white rust) on the surface. They are therefore usually given a chromate treatment, which is a chemical conversion process to cover the zinc surface with a hard non-porous film. This added coating effectively seals the surface and provides added corrosion protection. Chromate coatings are available in clear, iridescent or in a variety of colors.

Although not as resistant, phosphate coatings are also used for corrosion protection. The parts may be submerged in a diluted solution of phosphoric acid for forming a mildly protective layer of either crystalline iron, manganese or zinc phosphate. The nature of the crystals make phosphated part's surface readily painted by providing better adherence. They can also be dipped in oil or wax to improve their corrosion resistance. Hydrogen embrittlement is typically not encountered in phosphated parts. Zinc phosphate starts deteriorating around 225°F whereas iron phosphate can tolerate temperatures up to 375°F.

Nickel plating, with or without copper strike (thin under layer), is one of the most common techniques of preventing corrosion and improving the appearance of steels. It will most likely tarnish unless chromium plating is placed on top. Nickel plating process also requires a baking treatment to avoid hydrogen embrittlement. Although as high as 1000°F service temperatures can be tolerated, nickel plating is not frequently used because of the higher cost compared to other coatings.

Chromium plating is used for automotive and decorative appliance applications. It is also used as hard chrome plating for wear applications. Good quality chrome platings typically require copper and nickel platings prior to chrome plating. Hydrogen embrittlement is also a problem with this type plating.

Stainless steel fasteners may lead to galvanic corrosion or oxidation in a joint unless they are passivated before use. Passivation (acid treatment) results in removal of free iron from the surface of the fasteners that may have been picked up as a result of contact with ferrous tools during the fabrication process. It also facilitates formation of a protective, chromium-rich oxide film.

Black oxide coating that is used on carbon steel fasteners does little more than enhancing the appearance and therefore it is usually combined with an oil film to provide some corrosion protection.

Characteristics of various coatings along with their degree of corrosion protection are summarized in the table below:

Characteristics of Platings, Coatings and Finishes

Plating, Coating or Finish	For Use On	Degree of Corrosion Resistance	Characteristics
Rust inhibitors	All metals	Varies with type	Oils, greases, etc. Vary in color and film thickness. Usually applied to black oxide finishes. Used to protect parts in transit and temporary storage.
Zinc, electroplated	All metals	Very good	Blue to blue-white gray color.
Cadmium, electroplated	Most metals	Excellent	Bright silver-gray, dull gray, or black finish. Particularly effective corrosion protection in marine applications. Used for decorative purposes. High lubricity.
Clear chromate finish	Zinc and cadmium plated parts	Very good to excellent	Clear bright or iridescent chemical conversion coating applied to plated parts to enhance corrosion protection, coloring, and paint bonding.
Dichromate	Zinc and cadmium plated parts	Very good to excellent	Yellow, brown, green or iridescent colored coating same as clear chromate.
Color chromate finish	Zinc and cadmium plated parts	Very good to excellent	Olive drab, blue, gold, bronze, etc. Same as clear chromate.
Zinc or Manganese Phosphate	Steel	Good	Black in color. Added protection when oiled with a non-drying petroleum oil containing corrosion inhibitors. Good lubricity.
Color phosphate coatings	Steel	Superior to regular phosphate and oiled surfaces	Chemically produced color coating. Available in blue, green, red, purple, etc.
Hot-dip zinc	All metals	Very good	Gives maximum corrosion protection. Dull grayish color. Necessitates thread size adjustments to permit assemblability.
Hot-dip aluminum	Steel	Very good	Gives maximum corrosion protection. Dull grayish color. Necessitates thread size adjustments to permit assemblability.
Mechanically deposited Zinc	Steel	Very good	Dull gray, smooth finish. Corrosion protection depends on coating thickness. Good coverage in recesses and thread roots.
Tin, electroplated	All metals	Excellent	Silver-gray color. Excellent corrosion protection for parts in contact with food.
Hot-dip tin	All metals	Excellent	Same as electroplated but thickness is harder to control.
Lead-tin	Steel, usually	Fair to good	Silver-gray, dull coating. Applied by hot-dip method. Helps lubricity.
Silver, electroplated	All metals	Excellent	Decorative, expensive, excellent electrical conductor.
Chromium, electroplated	Most metals	Good (improves with copper and nickel undercoats)	Bright, blue-white, lustrous finish. Has relatively hard surface. Used for decorative purposes or to add wear resistance.
Copper, electroplated	Most metals	Fair	Used for nickel and chromium plate undercoat. Can be blackened and relieved to obtain Antique, Statuary, and Venetian finishes.
Brass, electroplated, lacquered	Steel, usually	Fair	Brass electroplated which is then lacquered. Recommended only for indoor decorative use.
Bronze, electroplated, lacquered	Steel, usually	Fair	Has color similar to 80% copper, 20% zinc alloy. Electroplated and then lacquered. Recommended only for indoor decorative use.
Copper, brass, bronze, miscellaneous finishes	Most metals	Indoor, very good	Decorative finishes. Applied to copper, brass, and bronze plated parts to match colors. Color and tone vary from black to almost the original color. Finish names are: Antique, Black Oxide, Statuary, Old English, Venetian, Copper Oxidized.
Bright nickel	Most metals	Indoor excellent. Outdoor good if thickness at least 0.0005 in.	Electroplated silver-colored finish. Used for appliances, hardware, etc.
Dull nickel	Most metals	Same as bright nickel	Whitish cast. Can be obtained by mechanical surface finishing or a special plating bath.
Lacquering, clear or color-matched	All metals	Improves corrosion resistance. Some types designed for humid or other severe applications	Used for decorative finishes. Clear or colored to match mating color or luster.
Anodizing	Aluminum	Excellent	Acid electrolytic treatment. Frosty-etched appearance. Hard oxide surface gives excellent protection.
Passivating	Stainless steel	Excellent	Chemical treatment. Removes iron particles and produces a passive surface.

Fastener Properties

Physical, mechanical and performance characteristics are material/process related and collectively define the fastener's service capability. Physical properties are inherent in the raw material and remain either unchanged or go though a slight alteration during the manufacturing process. Density, coefficient of thermal expansion, electrical resistivity, thermal conductivity, and magnetic properties are all important factors to consider for the specific application. Mechanical properties can be changed significantly through heat treatment.

Mechanical properties define how a fastener will react to applied loads. These are rarely the same as the raw material's. Tensile and yield strengths, hardness and ductility are all subject to significant change dependent on the manufacturing methods and thermal treatments. Raw material selection is important in achieving the finished product's properties.

Performance properties designed into the fastener satisfy requirements of the service application. Properties such as locking ability, prevailing torque, sealing, driving torque are all gained by control of dimensional features during manufacturing.

Fastener strength grades, each with its own defined mechanical properties, are well established for steel and documented in various standards. The most common publications are by ASTM, SAE, ISO and IFI. The testing procedures are also standardized and can be found in ASTM Standard F606. Tensile strength is the maximum load a fastener can support in tension prior to its fracture. They are normally expressed in pounds per square inch (psi). The load value expressed in pounds can be determined by multiplying the effective stress area of threads (listed in fastener standards) by the stress. It is desirable to test the fasteners full size as long as the strength and size limitations allow it. For larger size or higher strength fasteners, a machined specimen may be used as indicated in the testing specifications. Some fastener specifications (i.e. hex head bolts) require the tensile testing to be performed with a wedge. In wedge tensile tests a hardened washer with a specified angle beveled surface is placed under the head of the fastener. As the load is applied, the wedging action induces a severe bending stress that is concentrated at the head-to-shank junction. To be acceptable the fastener must be able to support the minimum tensile strength without failure. Additionally, the fracture has to occur away from this junction area. This confirms that the fastener has sufficient ductility and integrity at the critical head-to-shank juncture as shown in the example below (Figure 1). The wedge angle varies between 4 to 10 degrees dependent on fastener size, strength grade, head style and closeness of threading to the head.

Yield strength corresponds to a load where a fastener starts to experience permanent deformation (i.e. stressed beyond its elastic limit). Yield strengths of machined specimens are easily determined with an extensometer because of their uniform cross-sectional area throughout the stressed length. Unfortunately, when test specimens are used, they do not accurately reflect the yield strength of the full size product since the beneficial effects of cold working around the threads are lost along with the potential detrimental effects of the threads (acting as stress concentrations). Since it is difficult to test finished fasteners for yield strength, a more convenient "proof load" concept is utilized.

Proof load is a tension load that a fastener must support without any permanent deformation. It is an absolute value, not a minimum or maximum. In proof load testing the overall length of the fastener is measured, the specified proof load applied and held for the designated duration, released and the length remeasured. To be acceptable, the after loading length should be same as the original length (within a small tolerance to account for measurement error). This confirms that the material's yield point has not been exceeded. For most fastener strength grades, proof loads are established at approximately 90 percent of the expected yield strength of the fastener material.

Hardness is a measure of a material's ability to resist abrasion. The importance of hardness as a specification requirement is that hardness testing is quick, relatively easy and most of the time can be performed nondestructively. It also correlates well with tensile strength. Hardnesses are typically expressed in terms of Rockwell or Brinell values. Conversion tables have been developed for steels as shown below.

Figure 1. Photograph of a bolt after tensile testing, failure occurred in a ductile manner in the threaded section away from the head to shank junction area.

Table 1 Tensile Strength & Hardness Relationships for Carbon Steel Fasteners

Tensile Strength (Approx.) ksi	Rockwell Hardness No. B Scale	Rockwell Hardness No. C Scale	Rockwell Hardness No. 30-N Scale	Brinell Hardness No.	Vickers Hardness No.
56	65.7	—	—	111	117
60	69.8	—	—	121	127
65	74.0	—	—	131	137
71	78.7	—	—	143	150
76	82.9	—	—	156	163
81	86.0	—	—	167	175
85	87.8	—	—	174	182
90	90.7	—	—	187	196
95	92.8	—	—	197	207
100	94.6	—	—	207	218
105	96.4	—	—	217	228
110	97.8	20	41.5	226	238
114	99.0	22	43.2	237	248
117	100.0	23	44.0	243	254
120	—	24	45.0	247	260
122	—	25	45.9	253	266
125	—	26	46.8	258	272
128	—	27	47.7	264	279
132	—	28	48.6	271	286
135	—	29	49.5	279	294
138	—	30	50.4	286	302
142	—	31	51.3	294	310
145	—	32	52.1	301	318
149	—	33	53.3	311	327
153	—	34	54.2	319	336
157	—	35	55.0	327	345
162	—	36	55.9	336	354
168	—	37	56.8	344	363
171	—	38	57.7	353	372
176	—	39	58.6	362	382
181	—	40	59.5	371	392
188	—	41	60.4	381	402
194	—	42	61.3	390	412
201	—	43	62.2	400	423
208	—	44	63.1	409	434
215	—	45	64.0	421	446
222	—	46	64.8	432	458

NOTE: Approximate tensile strengths and hardness value relationships are abstracted from conversion tables included in SAE Information Report J417

In most fastener standards a hardness range is specified for the specific grade. The minimum hardness corresponds to the minimum tensile strength, and the maximum to a level of hardness beyond which the fastener may be considered brittle. For routine testing the measurements may be made on the hex flats, the unthreaded shank or on the end of the product. When referee testing is necessary, hardness is measured at mid-radius of a cross section one diameter from the end of the product (this then becomes a destructive test). For quenched and tempered steel fasteners it is desirable to measure the hardness at the surface and compare to that of the core. A lower surface value suggests presence of decarburization-a soft surface layer caused by loss of carbon at the surface during heat treatment. If the surface is harder than the core, then this may signal carburization, a condition that may lead to a brittle surface layer. Neither condition is desirable and may cause performance issues in service.

Ductility of the fastener is also important and the criteria for evaluation are elongation (%E) and reduction of area (%RA). Both can be easily determined if a machined specimen is tested. If full size samples are tested then measurement is not practical most of the time since the failures occur in the threaded area. If the fastener hardness does not exceed the maximum hardness and passes the wedge tensile test then the fastener can be considered as having acceptable ductility.

Shear strength of a fastener is the maximum load applied normal to the fastener axis, that can be supported prior to failure. This property can be tested either by single or double shear methods and are most commonly specified for aerospace applications. As an empirical guide, shear strength of carbon steel fasteners may be assumed to be approximately 60 percent of their tensile strengths.

Torsional strength is usually expressed in terms of applied torque (e.g. ft-lbs) at which a fastener fails by being twisted off about its axis.

Fatigue strength is the maximum load a fastener can be subjected to for a specified number of repeated load applications prior to its failure. The magnitude of the applied load and the number of cycles to failure are closely related. As the load is reduced, the fastener endures an increasing number of loading cycles until it reaches a certain fatigue strength level. This is known as the endurance limit, a load level where a fastener can survive indefinite number of load cycles. Fasteners used in aerospace applications are frequently fatigue strength rated, whereas ones in industrial applications are practically never rated for fatigue.

Nuts are also proof load tested just like the bolts. Upon release of the axial tension load application the nut must be capable of being freely removed from the test mandrel. This demonstrates that insufficient thread distortion has occurred. Nut proof loads are typically expressed in terms of stress (psi). To compute the actual proof load in pounds, the psi should be multiplied by the thread area. Hardness, although a very important mechanical property for nuts, unlike bolts does not provide a definitive relationship in regards to nut strength. The reason is the allying influence of nut geometry on nut strength. Nut heights and wall thicknesses relate directly to load carrying capacity. Nut height establishes the length of thread engagement, wall thickness establishes resistance to radial spreading out at the nut's bearing surface.

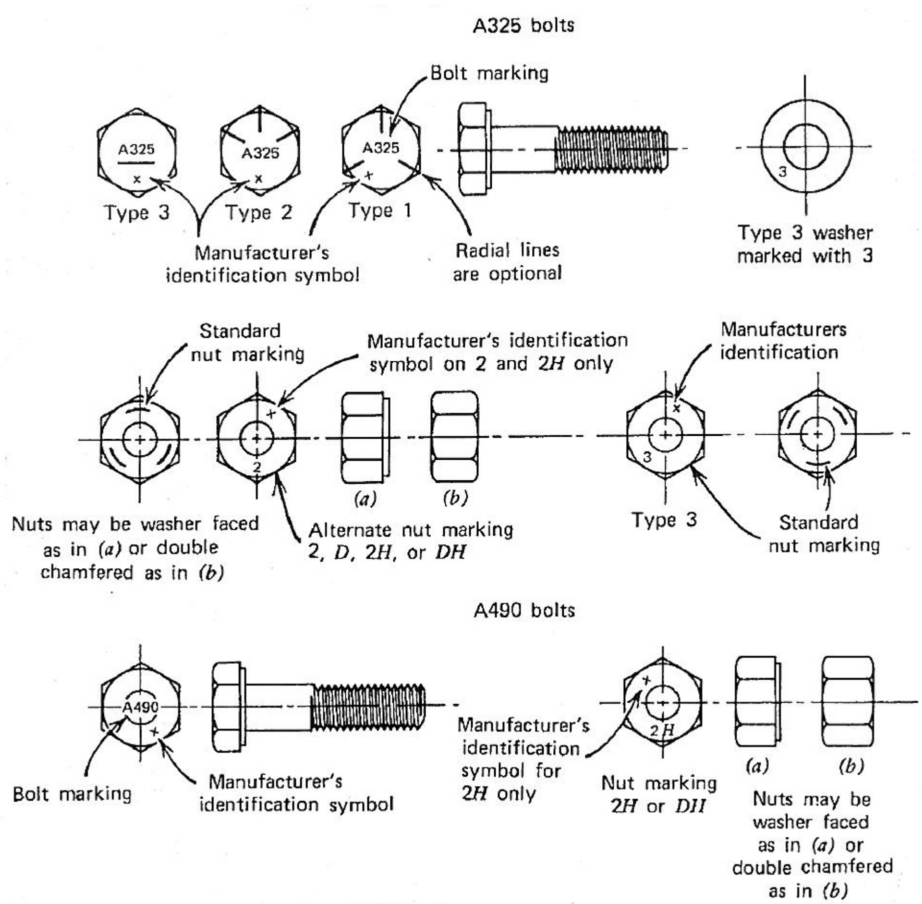
Strength Grade Systems and Identification Markings

There are numerous standard strength grades for carbon steel externally threaded fasteners. Each has its own mechanical properties, designations and identification markings. The most widely referenced strength grade system is that of the SAE (Society of Automotive Engineers). The system comprises of low carbon steel Grade 1 through alloy steel Grade 8. The below table summarizes the basic materials, mechanical properties, designations and grade identification markings of the SAE and ASTM grades. In the SAE system grades are designated by numbers from 1 to 8.2. These numbers do not have a quantitative relationship to strength properties, except that increasing numbers represent increasing tensile strengths. Decimals after the whole numbers indicate the same basic properties, with variations in either material or processing treatment. ASTM grades are designated by their document number (e.g. ASTM A325). The most commonly used types of structural bolts are 1)

ASTM A307 low carbon steel bolt, 2) ASTM A325 high-strength steel bolt made from medium carbon steel and heat treated and 3) ASTM A490 quenched and tempered alloy steel bolt.

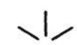
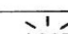
It is a mandatory requirement in SAE and ASTM standards that fasteners of the medium carbon and alloy steel strength grades be marked for grade identification (see below examples). The only exceptions are slotted and recessed head screws and very small size fasteners-generally smaller than 1/4" where head size does not allow marking. Additionally, these same standards require all fasteners be further marked to identify the manufacturer. Markings provide traceability and accountability.

SAE Grade 2 nuts need not be marked. SAE Grades 5 and 8 nuts are required to be grade identified, using the clock marking system. A dot is located at one corner on the top surface to indicate 12 o'clock, and a radial line is placed at the 5 and 8 o'clock position to identify Grades 5 and 8 nuts respectively. For any low-carbon, non heat treated bolt, any strength grade nut is adequate. For medium carbon and alloy steel bolts, any nut with a specified proof stress equal to or greater than the specified minimum tensile strength of the externally threaded fastener should perform satisfactorily. If absolute safety is a design prerequisite, a nut with a specified proof stress about 20 percent greater than the specified minimum tensile strength of the mating bolt should be selected. Good design dictates that if a bolt/nut combination should fail, either through over tightening during installation or overloading in service, that effort be made to assure the failure is bolt fracture and not thread stripping.



Bolt markings for high-strength bolts.

Mechanical Requirements for Carbon Steel Externally Threaded Fasteners

Grade Designation	Nominal Size of Product in.	Material and Treatment	Mechanical Requirements: Proof Load Stress ksi	Mechanical Requirements: Yield Strength ksi Min	Mechanical Requirements: Tensile Strength ksi Min	Product, Hardness, Rockwell: Surface Max	Product, Hardness, Rockwell: Core Min	Product, Hardness, Rockwell: Core Max	Grade Identification Marking
A307 Gr. A	1/4 to 4	low or medium carbon steel	—	—	60	—	B69	B100	None Specified
A307 Gr. B	1/4 to 4		— —	— —	60 min 100 max	—	B69	B95	
SAE Gr. 1	1/4 to 1-1/2		33	36	60	—	B70	B100	
SAE Gr. 2	1/4 to 3/4	low or medium carbon steel, cold worked	55	57	74	—	B80	B100	None Specified
SAE Gr. 5	1/4 to 1 1-1/8 to 1-1/2	medium carbon steel; the product is quenched and tempered	85 74	82 81	120 105	30N54 30N50	C25 C19	C34 C30	
A449 Type 1	1/4 to 1 1-1/8 to 1-1/2 1-3/4 to 3		85 74 55	92 81 58	120 105 90	— — —	C25 C19 B91	C34 C30 B100	
A325 Type 1	1/2 to 1 1-1/8 to 1-1/2		85 74	92 81	120 105	— —	C24 C19	C35 C31	A325
SAE Gr. 5.2	1/4 to 1	low carbon boron steel; the product is quenched and tempered	85	92	120	30N56	C26	C36	
A449 Type 2	1/4 to 1		85	92	120	—	C25	C34	
A325 Type 2	1/2 to 1		85	92	120		C24	C35	 A325
	1-1/8 to 1-1/2		74	81	105		C19	C31	
A325 Type 3	1/2 to 1	atmospheric corrosion resistant steel; the product is quenched and tempered	85	92	120	—	C24	C35	A325
	1-1/8 to 1-1/2		74	81	105	—	C19	C31	
SAE Gr. 8	1/4 to 1-1/2	medium carbon alloy steel; the product is quenched and tempered	120	130	150	30N58.6	C33	C39	
A354 Gr. BD	1/4 to 2-1/2		120	130	150	—	C33	C39	
	2-3/4 to 4		105	115	140	—	C31	C38	
A490 Type 1	1/2 to 1-1/2		120	130	150 min 170 max	— —	C33	C38	A490
SAE Gr. 8.2	1/4 to 1	low carbon boron steel; the product is quenched and tempered	120	130	150	30N58.6	C33	C39	
A490 Type 2	1/2 to 1		120	130	150 min 170 max	—	C33	C38	A490
A490 Type 3	1/2 to 1-1/2	atmospheric corrosion resistant steel; the product is quenched and tempered	120	130	150 min 170 max	—	C33	C38	A490
See Note: 1, 4			2	2	2				3

NOTES:

1. For titles and sources of availability for referenced ASTM and SAE standards refer to page M-28. For ASTM A307, see page B-58. For ASTM A449, see page B-63. For ASTM A325, see page E-11. For ASTM A354, see page B-68. For ASTM A490, see page E-18. For SAE J429, see page B-50.
2. To compute the proof load, yield strength or tensile strength, in pounds, for a bolt, screw or stud, multiply the stress value, ksi, as given in Table 2 for the strength grade by 1000 and multiply this answer by the tensile stress area of the product's screw thread as given in Tables 1, 2 and 3 of ANSI/ASME B1.1, pages A-30, A-31 and A-32.
3. In general, identification markings shall be located on the top of the product head and preferably shall be raised.
4. SAE Grade 2 products are available in lengths 6 in. and shorter only.

Galling and Seizing

Galling occurs during fastener tightening. Seizing may happen in two ways. One is a direct consequence of galling, the other occurs in service and is not a problem until disassembly is attempted. Thread galling appears to be most prevalent among stainless steel, aluminum, titanium and other alloys which self generate an oxide surface film for corrosion protection. During fastener tightening, as pressure builds between the contacting and sliding thread surfaces, protective oxides are broken and high points on the interface lock together. This increasing adhesion leads to galling and possibly seizing. If tightening is continued, the fastener can be twisted off or threads stripped out. Thread lubrication is the most effective in relieving potential galling. However, addition of lubricant introduces other concerns. Not only the torque-tension relationships are altered, if the lubricant is too "slippery" then loosening becomes easier under vibration. Also, compatibility of the lubricant with the service environment should be evaluated. One simple example is stainless steel fasteners that are used in food processing equipment; they cannot be used with an organic lubricant. Parts of dissimilar alloys, and having different hardnesses, usually have fewer tendencies to gall than mating parts of the same alloy. Typically the smoother the surface texture, the less the frictional resistance. Rolled threads, which is the most common thread manufacturing practice for externally threaded fasteners that are 1 inch and smaller, are relatively smooth. External threads, which are cut, and internal threads, which are tapped, are considered to be rougher. Additionally since heat contributes to galling, higher installation speeds can be detrimental.

Thread seizures can occur after a period of time due to exposure to service environment. If periodic fastener removal is necessary for maintenance or inspection then avoiding this possibility is advisable. The principal cause of seizures is corrosion. Oxidation products are greater in volume and can fill up the available space between the threads causing them to jam together. In such situations the effects of corrosion should be minimized with proper material selection or using appropriate coatings or platings. Use of a long-life lubricant can also help.

Thread Lubricants

The most common lubricants are oil, grease or wax, graphite, and molybdenum disulfide. There are also several proprietary lubricants such as Never-seez, and Loctite (used as thread locking compound).

Oil and grease being the most common types of thread lubricant, can be used up to 250°F. They cannot be used in a vacuum environment. They are good for both lubrication and corrosion protection.

Graphite is fine carbon powder used mixed with oil and water. This limits the maximum operating temperature, it also cannot be used in a vacuum environment. Since dry graphite is abrasive, its use is detrimental to the joint if these limitations are exceeded.

Molybdenum disulfide is one of the most popular dry lubricants. It can be used in a vacuum environment but turns to molybdenum trisulfide and becomes an abrasive rather than a lubricant at approximately 750°F.

Never-seez is a proprietary petroleum-based lubricant and anticorrodent that can be used up to 2000°F. The oil boils off at high temperatures but the compound leaves nongalling oxides of nickel, copper and zinc between the threads. This allows the fastener to be removed if needed but a new application is required each time the fastener is installed.

Corrosion

Galvanic corrosion mechanism becomes active when two dissimilar metals are coupled in the presence of an electrolyte, such as moisture. The galvanic cell that is created causes the most active (anodic) of the two materials to corrode in favor of the less noble one (the cathode). The farther apart the two materials are in the following list the greater the galvanic action between them. Note the difference between active and passive 304 and 316 stainless steels; the passive ones have the inert oxide layer on their surfaces deterring galvanic activity.

Galvanic series in seawater at 25 °C (77 °F)

Corroded end (anodic, or least noble)

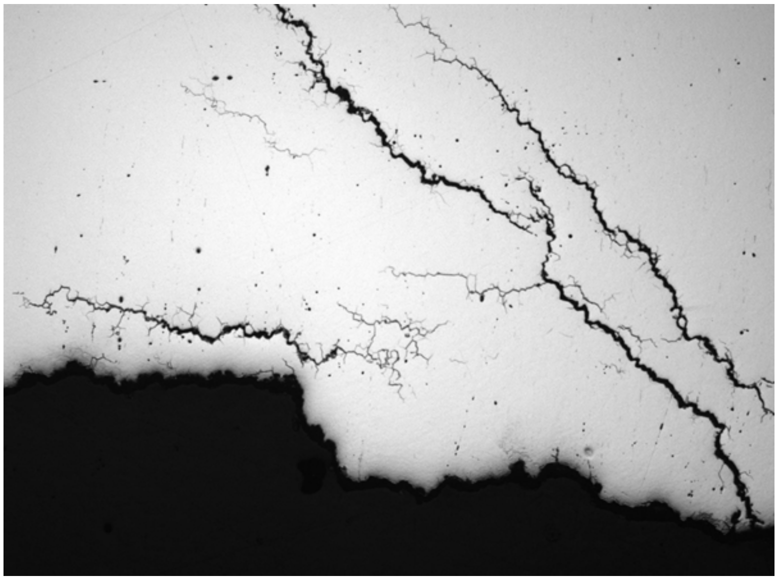
Magnesium
Magnesium alloys
Zinc
Galvanized steel or galvanized wrought iron
Aluminum alloys
5052, 3004, 3003, 1100, 6053, in this order
Cadmium
Aluminum alloys
2117, 2017, 2024, in this order
Low-carbon steel
Wrought iron
Cast iron
Ni-Resist (high-nickel cast iron)
Type 410 stainless steel (active)
50-50 lead-tin solder
Type 304 stainless steel (active)
Type 316 stainless steel (active)
Lead
Tin
Copper alloy C28000 (Muntz metal, 60% Cu)
Copper alloy C67500 (manganese bronze A)
Copper alloys C46400, C46500, C46600, C46700 (naval brass)
Nickel 200 (active)
Inconel alloy 600 (active)
Hastelloy alloy B
Chlorimet 2
Copper alloy C27000 (yellow brass, 65% Cu)
Copper alloys C44300, C44400, C44500 (admiralty brass)
Copper alloys C60800, C61400 (aluminum bronze)
Copper alloy C23000 (red brass, 85% Cu)
Copper C11000 (ETP copper)
Copper alloys C65100, C65500 (silicon bronze)
Copper alloy C71500 (copper nickel, 30% Ni)
Copper alloy C92300, cast (leaded tin bronze G)
Copper alloy C92200, cast (leaded tin bronze M)
Nickel 200 (passive)
Inconel alloy 600 (passive)
Monel alloy 400
Type 410 stainless steel (passive)
Type 304 stainless steel (passive)
Type 316 stainless steel (passive)
Incoloy alloy 825
Inconel alloy 625
Hastelloy alloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum

Protected end (cathodic, or most noble)

Because the anode is eroded in a galvanic cell, it should be the larger mass if coupling of dissimilar metals cannot be avoided in design. Using carbon steel fasteners in a stainless steel or copper assembly is considered poor design practice. Stainless fasteners can be used in carbon steel assemblies since the larger mass is the anode.

Magnesium is used in lightweight designs because of its high strength to weight ratio. However, it must be totally isolated from any other metal by an inert coating to prevent extremely galvanic corrosion. Cadmium or zinc plated fasteners are closest to magnesium in the galvanic series and would be the most compatible if the insulation coating is damaged.

Stress corrosion cracking (SCC) occurs when a part under applied or residual stress is placed in a corrosive environment. An otherwise ductile part can fail in a brittle manner at a stress level that is much lower than its yield strength because of cracks that can develop as a result of exposure to the corrosive environment. The fastener material manufacturers have been required to develop alloys that are less sensitive to stress corrosion cracking. Of the stainless steels, A286 is the best alternative for aerospace use. Fasteners made out of duplex stainless steels, superalloys such as Inconel 718 or MP35N are also available if cost is not a limiting factor. Although it is a progressive failure mechanism, since SCC occurs with little or no deformation, detecting it may be almost impossible unless nondestructive inspections are performed periodically. Annual ultrasonic inspections carried out in a paper plant was able to detect the cracks that developed in the below bolts in a caustic environment.



Micrograph showing branched, intergranular stress corrosion cracks

Considering that there are no design limitations, sometimes it is preferable to use more ordinary variety fasteners than a few high strength ones. High strength fasteners (greater than 180,000 psi) bring on problems such as brittleness and susceptibility to various failure mechanisms. Nondestructive quality control procedures such as magnetic particle, fluorescent penetrant inspections, thread and head radius verifications are commonly used for fasteners in critical applications.

Hydrogen embrittlement occurs whenever the metal is exposed to environments that contain free hydrogen. Since most plating processes are the electrolytic bath type, free hydrogen is present. There are mainly three types of hydrogen related problems in metals:

A) Hydrogen chemical reaction: Hydrogen reacts with the carbon in steel to form methane gas, which can lead to crack development and strength reduction. Hydrogen can also react with alloying elements such as titanium, niobium, or tantalum to form hydrides. Because the hydrides are not as strong as the parent alloy, they reduce the overall strength of the part.

B) Internal hydrogen embrittlement: Hydrogen can remain in solution interstitially (between lattices in the grain structure) and can cause delayed failures under tensile load after the fastener is installed. This condition cannot be detected through conventional mechanical tests (tensile, proof load or hardness) and special sustained load tests have to be conducted to determine if it exists.

C) Hydrogen environment embrittlement: This problem is encountered during service in a moist environment if hydrogen is evolved or in a high-pressure hydrogen environment such as a hydrogen storage tank. Again the fastener has to be under stress exposed to a hydrogen-rich environment for this to be a problem.

Most plating specifications now state that a plated carbon steel fastener "shall be baked for not less than 23 hours at 375°F within 2 hours after plating to provide hydrogen embrittlement relief" (per MIL-N-25027D). In commercial applications there are guidelines given in ASTM standards as shown below that specify appropriate baking treatments based on fastener strength levels since embrittlement problems increase as the fastener strength increases.

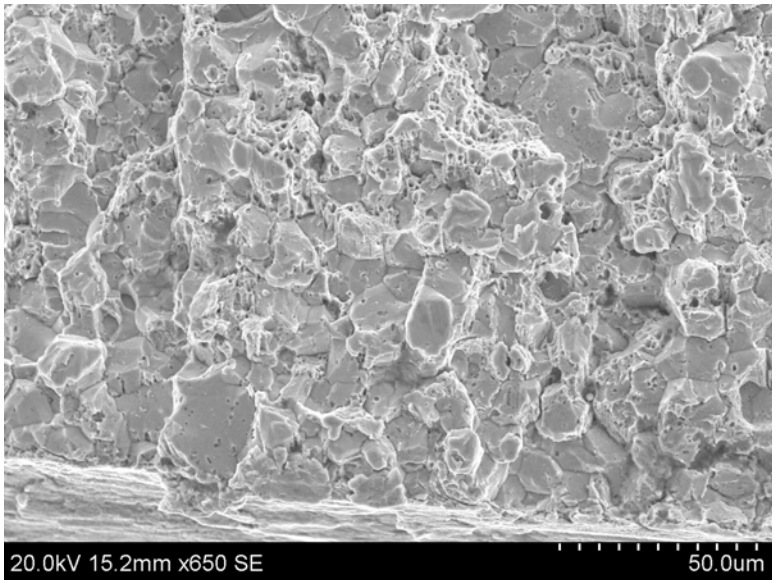
Classes of Embrittlement-Relief Heat Treatment

Hydrogen Embrittlement-Relief Treatment Classes for High-Strength Steels

Class	Steels of Tensile Strength (R_m), MPa	Temperature, °C	Time, h
ER-0	not applicable		
ER-1	1701 to 1800	190–220	min 22
ER-2	1601 to 1700	190–220	min 20
ER-3	1501 to 1600	190–220	min 18
ER-4	1401 to 1500	190–220	min 16
ER-5	1301 to 1400	190–220	min 14
ER-6	1201 to 1300	190–220	min 12
ER-7[A]	1525 or greater	177–205	min 12
ER-8	1101 to 1200	190–220	min 10
ER-9	1000 to 1100	190–220	min 8
ER-10[A]	1250 to 1525	177–205	min 8
ER-11[A]	1450 to 1800	190–220	min 6
ER-12[A]	1000 to 1500	177–205	min 4
ER-13	1000 to 1800 unpeened items and for engineering chromium plated items	440–480	min 1
ER-14[A]	surface-hardened parts <1401	130–160	min 8
ER-15[A]	surface-hardened parts 1401 to 1800 plated with cadmium, tin, zinc, or their alloys	130–160	min 8
ER-16	surface-hardened parts <1401 plated with cadmium, tin, zinc, or their alloys	130–160	min 16

[A]Classes ER-7, ER-10, ER-11, ER-12, ER-14, and ER-15 are traditional treatments used in Federal Standard QQ-C-320. They do not apply to any other standard.

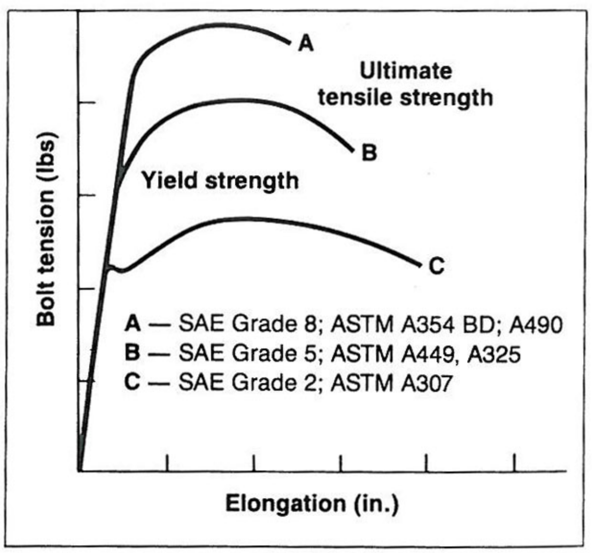
Similar to SCC, the crack surfaces of hydrogen embrittlement failures have a brittle, intergranular appearance as shown below.



Scanning Electron Micrograph of a bolt that failed due to hydrogen embrittlement

Fastener Installation/Torque

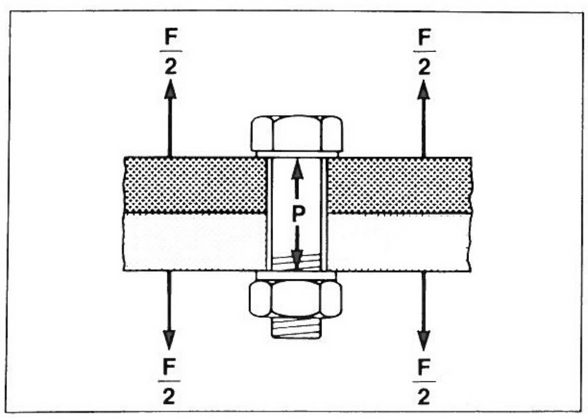
Threaded fasteners are tightened for the obvious reason of clamping parts together and transmitting loads. In gasketed joints, the purpose is to prevent leakage. In other joints, the clamping force is developed to prevent the parts from separating or shaking loose. When a bolt is tensile loaded, it elongates elastically until stressed beyond its proportional limit. It then yields and begins its plastic behavior. As tensile load increases, elongation continues but at a much faster rate until fracture occurs. Below figure illustrates typical load-elongation behavior of the three most popular strength grades of carbon steel bolts.



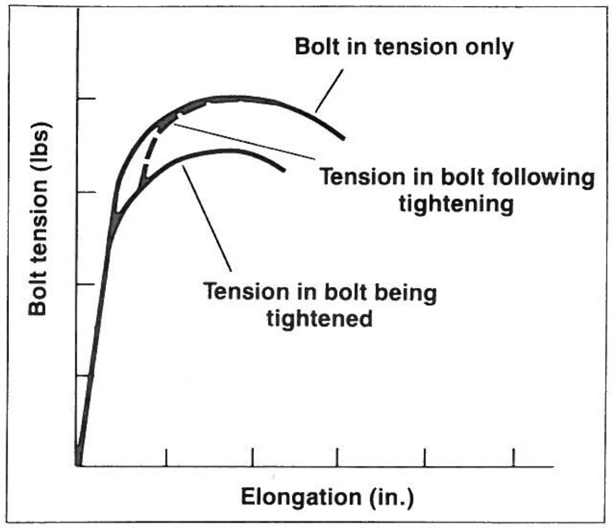
Typical load-elongation behavior of bolts in tension.

When a bolt is tightened in a joint as shown below, its load-elongation behavior is similar. But, because of a torsional stress component introduced by wrenching the bolt head or nut, the bolt yields and fractures at lower tensile stresses. This phenomenon is also illustrated in the figure below. The differential (reduction of tensile stress capacity due to torsional stresses) varies dependent on frictional factors, but generally approximates to 15 percent.

If a bolt is tightened in the same joint to a tensile stress less than that causing failure by tightening, and then the bolt is loaded in pure tension to failure. The load at fracture will equal that of the original bolt. The reason is that when wrenching is stopped the torsional component of the combined stress dissipates, leaving only the tensile component. This most valuable phenomenon means that after tightening, regardless of the initially induced tensile load in the bolt, a considerable residual tensile strength capacity remains. When a bolt/nut combination is tightened in a joint, because the fastener is restrained at its bearing surfaces, the bolt elongates and the joined material compresses. The tensile load developed in the bolt is known as its preload, and it squeezes the joined material together as though it had been placed in a vise. Following tightening, and before the application of any service loads, the joint is in equilibrium. The preload is balanced by the resistance of material against the bolt head and nut. The most common misconception in bolted joint analysis is that all of an external load applied in a joint-separating direction adds to bolt preload. What actually happens is that the external load is shared by adding some new tension into the bolt while simultaneously relieving some of the compression from the joint. The key point is that until there is joint separation, strains are equal. That is the bolt can only elongate, thus adding new tension, by an amount equal to the spring back of the joint as the compression is relieved. Separation of the joint-usually considered one of the criteria of failure-occurs when the external load is sufficient to relieve the entire compression load from the joint.



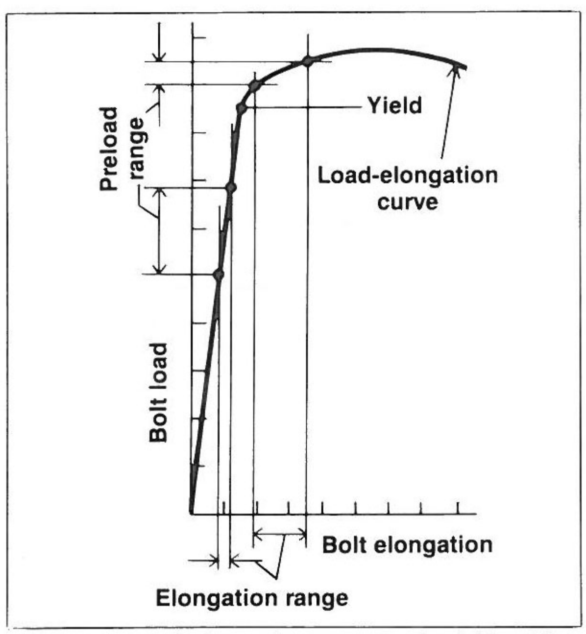
Bolted joint — externally loaded.



Load-elongation of bolts during and after tightening.

Bolts retain considerable tensile strength capacity following tightening, even if preloaded beyond their yield strength. So, tightening to yield optimizes preload without risking imminent failure. In any rigid joint, the higher the preload, the more protection against joint separation and slip and the less chance of fastener loosening due to vibration.

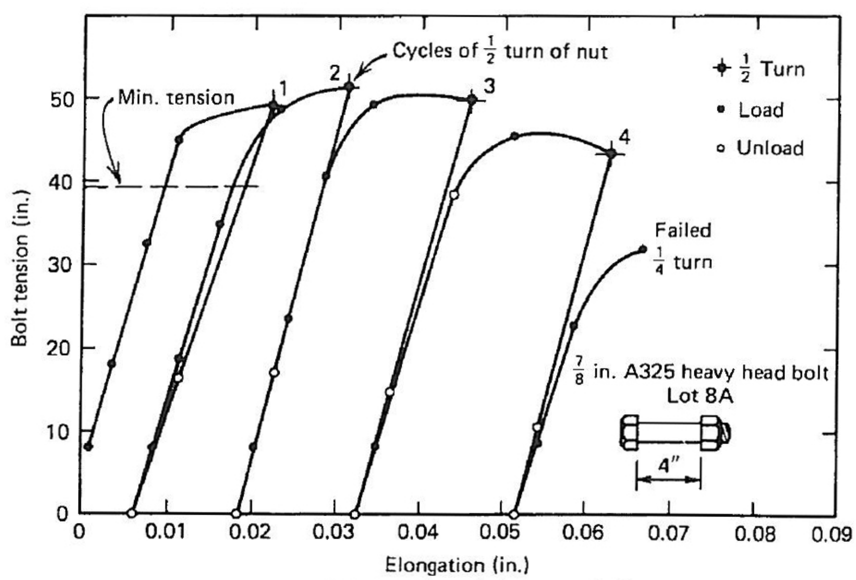
All joints suffer short term and long-term relaxation. Generally, residual preload of a tightened-to-yield bolt will exceed that of a bolt preloaded within its elastic range. Some of these relationships are illustrated in the figure below.



Typical elongation —preload relationships.

Fatigue strength of preloaded bolts, when exposed to the same cyclic stresses, generally remains unchanged as preload increases. Tightening to and beyond yield is advisable only for rigid joints with predictable stiffness properties. The magnitude and direction of externally applied loads should be analyzed carefully to assure that the higher preload is truly helpful and won't create a problem. Use of high strength fasteners with good ductility is best (e.g. Grades 5 and 8). It is important to evaluate environmental exposure conditions since high strength materials stressed to high load levels have susceptibility to stress corrosion cracking. Also any differences in the coefficients of thermal expansion of the joint material and fastener can introduce complications.

All high strength fasteners are installed so as to provide a preload equal to 70 percent of the minimum specified tensile strength of the bolt. The requirement now is that only fasteners that are to be used in slip-critical connections or in connections subject to direct tension need to be preloaded to this level. Bolts to be used in bearing-type connections need only be tightened to the snug-tight condition. The most common way of tightening fasteners is by turning either the nut or the bolt head. Since turn-of-nut method is likely to induce a bolt tension that exceeds the elastic limit of the threaded portion, repeated tightening of high strength bolts may be undesirable. Tests performed to examine the behavior of A325 bolts after torquing one-half turn, loosening, and then retorquing yielded results shown below. The cumulative plastic deformations after each succeeding installation eventually caused the failure of the bolt. This indicates that A325 bolts should not be reused more than twice.



Repeated installation A325 bolts.

In general there are three basic ways to control the amount of preload developed in a bolt during tightening; by measuring the tightening torque, by measuring bolt elongation (strain), and by measuring bolt load (stress). The first is an indirect relationship, and the latter two are direct measurements of change in bolt properties. It is impossible to avoid preload scatter. Even if every effort were made to make all installations as identical as possible, the range would most likely be plus or minus 10 percent from the average. The variations are caused by unavoidable slight differences in properties among the fasteners, surface texture, lubricity, tool performance variables, and operator inconsistencies. To help minimize friction variations, many critical applications employ a run-down, back-off, then run-down technique to allow the fastener and joint assembly to be polished prior to the final run-down to clamp. This method helps to ensure a more repeatable set of friction characteristics when torque-only specifications are used.

The information most frequently requested by fastener users involves tightening torques and the most popular preload control method in practice today is the torque measurement.

Determining the proper torque for a fastener is the biggest problem in fastener installation. Some of the many variables causing problems are:

- The coefficient of friction between mating threads
- The coefficient of friction between the bolt head (or nut) and its mating surface
- The effect of bolt coatings and lubricants on the friction coefficients
- The percentage of bolt tensile strength to be used for preload
- Relative spring rates of the structure and the bolts
- Interaction formulas to be used for combining simultaneous shear and tension loads on a bolt
- Whether "running torque" for a locking device should be added to the normal torque

When bolts are tightened they become stressed in tension. Analysis shows that approximately 50% of the tightening torque applied is needed to overcome the friction between the nut (or bolt head) turning against the joint surface. Another 40% is consumed overcoming friction between the mating threads. The remaining 10% develops useful tension in the bolt. Complicated mathematical formulas can be structured to describe the relationship between torque applied and tension developed. Fortunately, by introducing a few assumptions, these formulas reduce to the empirical version that is widely used:

$$T = K\ D\ P$$

Where

T= tightening torque, lbs-in

K= torque coefficient, unitless

D= nominal fastener diameter, in.

P= bolt tensile load, lbs.

The value K is not a coefficient of friction. Rather, it is a convenient catch-all constant encompassing the many factors and features influencing the torque-tension relationship. Each factor, for example, bearing area, thread series, material hardness, surface texture, has some modest effect. However, by far the most predominant influence is the coefficient of friction. As the COF lowers, the value of K also is reduced. This means that with the same applied torque a higher preload is developed. Or, conversely, less torque is needed to induce the same tension.
For clean, non-plated steel bolts in their as-received condition, K is about 0.20. For cadmium plated bolts, because of the good lubricity of cadmium, K drops to 0.17. Zinc plating roughens the surface; consequently K may be about 0.22 for zinc electroplated fasteners and 0.25 for hot-dipped galvanized ones. For bare steel fasteners exposed to the elements that may have oxidized, K may be 0.30 or higher. Extreme pressure waxes, such as those typically supplied with prevailing torque nuts, reduce K to about 0.10. Other proprietary platings and special coatings now commercially available lower K below 0.10. Taking all fastener surface conditions into account, the value of K ranges from about 0.35 to 0.06.

Assuming 1/2-13 SAE grade 5 bolts are to be preloaded to an initial tension of 9600 lbs. If the designer expects the bolts to be plain (non-plated) in their as-received condition, then tightening torque would be computed to be 80 lb-ft. (T= 0.20 x 0.5 x 9600 / 12). If, by chance, the bolts actually delivered and used are zinc plated, and if tightened with 80 lb-ft of torque, the preload drops to 8700 lbs. Conversely if the delivered bolts are coated with a lubricant, the bolts may break before a tightening torque of 80 lb-ft is reached.

The torque-tension formula is useful in determining a target value. However, the only sure way to establish the accurate torque is through experimentation using actual fasteners in the actual joint and testing and gathering data with strain measuring techniques. Another important factor is the installation tooling (torque wrenches). They should be monitored and periodically calibrated to verify their accuracy.

Locking Methods

There are various types of locking elements, with the common principle being to bind (or wedge) the nut thread to the bolt threads to provide extra resistance to vibration loosening. Locknuts fall into two general classes; prevailing-torque (nuts with out of round holes, nylon locking collar in nut, nylon patch, mechanically deformed dimples or crimps) and free-spinning (spring head nut, beam type nut, serrated nut bearing surface). Prevailing-torque nuts spin freely for a few turns, and then must be wrenched to the final position. Free-spinning locknuts spin on the bolt until seated. Additional tightening locks the nut. Some of these more common locknuts are covered below:

Split beam (Figure 2): The split-beam locknut has slots in the top, and the thread diameter is undersized in the slotted portion. The nut spins freely until the bolt threads get to the slotted area. The split "beam" segments are deflected outward by the bolt, and a friction load results from binding of the mating threads.

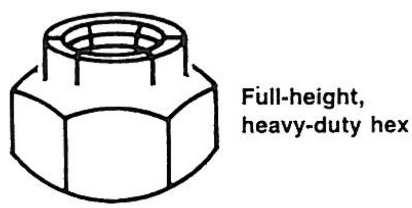


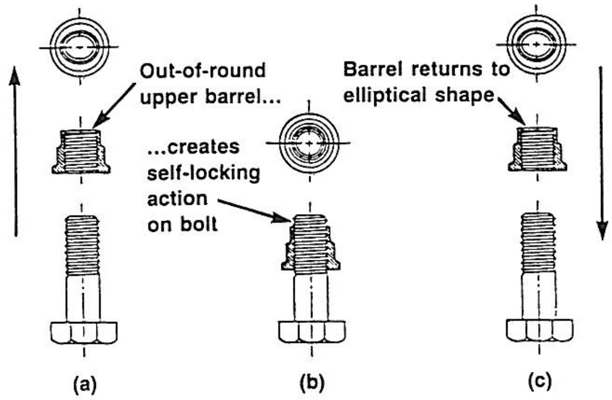
Figure 2.—Split-beam locknut.

Deformed thread (Figure 3): The deformed-thread locknut is a common locknut, particularly in the aerospace industry. Its advantages are as follows:

-1. The nut can be formed in one operation.

-1. The temperature range is limited only by the parent metal, its plating, or both.

-1. The nut can be reused approximately 10 times before it has to be discarded for loss of locking capability.



(a) Before assembly.
(b) Assembled.
(c) After withdrawal.

Figure 3.—Deformed-thread locknut.

Nylok pellet. The Nylok pellet (of nylon) is usually installed in the nut threads as shown in Figure 4. A pellet or patch projects from the threads. When mating threads engage, compression creates a counter-force that results in locking contact. The main drawback of this pellet is that its maximum operating temperature is approximately 250°F. The nylon pellet will also be damaged quickly by reassembly and can not be reused.

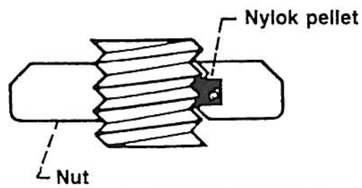


Figure 4.—Nylok pellet locknut.

Locking collar and seal. A fiber or nylon washer is mounted in the top of the nut as shown in Figure 5. The collar has an interference fit such that it binds on the bolt threads. It also provides some sealing action from gas and moisture leakage. Once again the limiting feature of this nut is the approximate 250°F temperature limit of the locking collar.

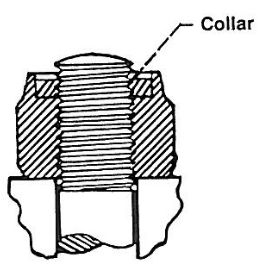
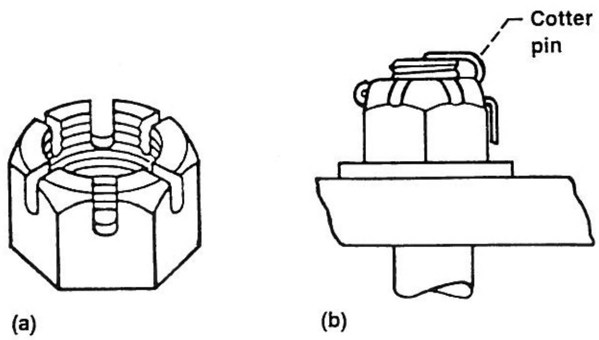


Figure 5.—Locking collar.

Castellated nut. The castellated nut normally has six slots as shown in Figure 6 (a). The bolt has a single hole through its threaded end. The nut is torqued to its desired torque value. It is then rotated forward or backward (depending on the user's preference) to the nearest slot that aligns with the drilled hole in the bolt. A cotter pin is then installed to lock the nut in place as shown in Figure 6 (b). This nut works extremely well for low-torque applications such as holding a wheel bearing in place.



(a) Slots.
(b) Cotter pin locking.

Figure 6.—Castellated nut.

Jam nuts. These nuts are normally "jammed" together as shown in Figure 7, although the "experts" cannot agree on which nut should be on the bottom. However, this type of assembly is too unpredictable to be reliable. If the inner nut is torqued more tightly than the outer nut, the inner nut will yield before the outer nut can pick up its full load. On the other hand, if the outer nut is tightened more than the inner nut, the inner nut unloads. Then the outer nut will yield before the inner nut can pick up its full load. It would be rare to get the correct amount of torque on each nut. A locknut is a much more practical choice than a regular nut and a jam nut. However, a jam nut can be used on a turnbuckle, where it does not carry any of the tension load.

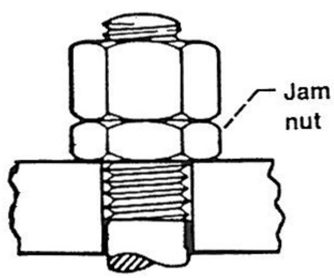


Figure 7.—Jam nut.

Serrated-face (durlock) nut (or bolt head). The serrated face of this nut (shown in Figure 8) digs into the bearing surface during final tightening. This means that it cannot be used with a washer or on surfaces where scratches or corrosion could be a problem.

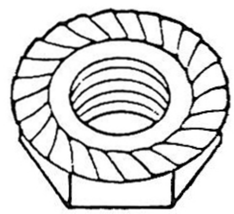
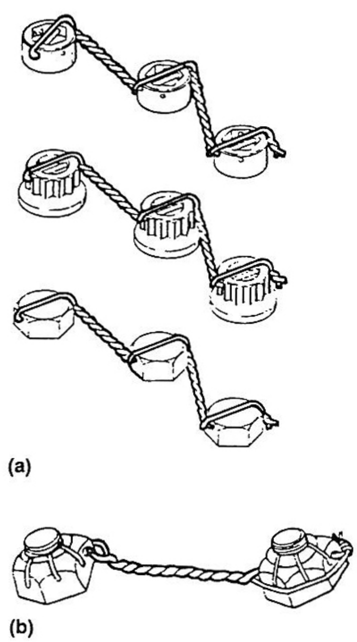


Figure 8.—Durlock nut.

Lockwiring. Although lockwiring is a laborious method of preventing bolt or nut rotation, it is still used in critical applications, particularly in the aerospace field. The nuts usually have drilled corners, and the bolts either have through-holes in the head or drilled corners to thread the lockwire through. A typical bolt head lockwiring assembly is shown in Figure 9 (a), and a typical nut lockwiring assembly is shown in Figure 9 (b).



(a) Multiple fastener application (double-twist method, single hole).
(b) Castellated nuts on undrilled studs (double-twist method).

Figure 9.—Lockwiring.

Direct interfering thread. A direct interfering thread has an oversized root diameter that gives a slight interference fit between the mating threads. It is commonly used on threaded studs for semi-permanent installations, rather than on bolts and nuts, since the interference fit does damage the threads.

Tapered thread. The tapered thread is a variation of the direct interfering thread, but the difference is that the minor diameter is tapered to interfere on the last three or four threads of a nut or bolt as shown in Figure 10.

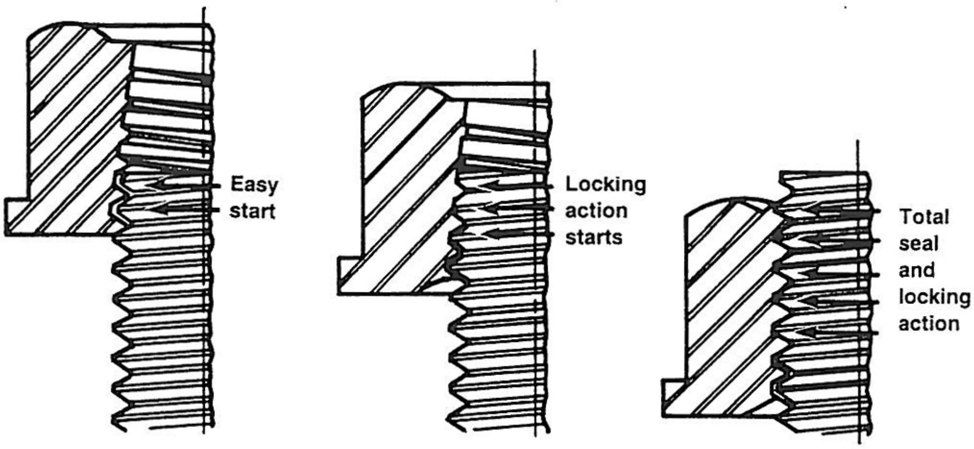
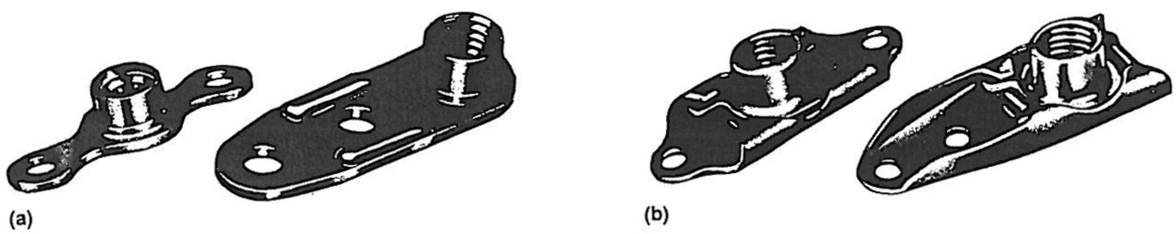


Figure 10.—Tapered thread.

Nutplates. A nutplate (Figure 11) is normally used as a blind nut. They can be fixed or floating. In addition, they can have most of the locking and sealing features of a regular nut. Nutplates are usually used on materials too thin to tap. Primarily the aerospace companies use them, since their installation is expensive. At least three drilled holes and two rivets are required for each nutplate installation.



(a) Fixed.
(b) Floating.

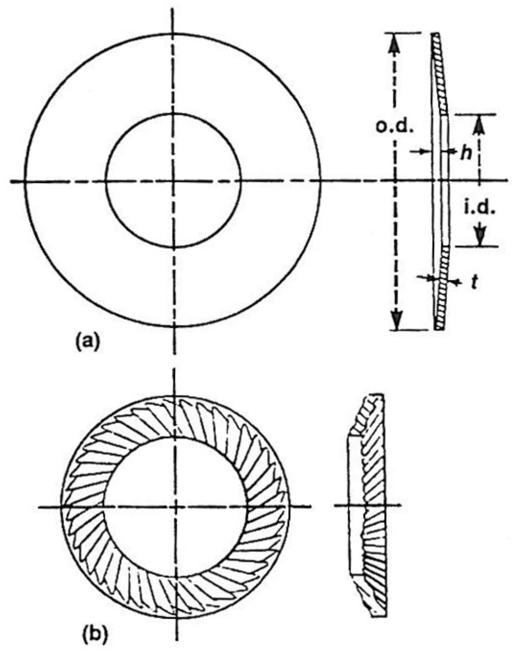
Figure 11.—Nutplate.

Locking Adhesives

Many manufacturers make locking adhesives (or epoxies) for locking threads. Most major manufacturers make several grades of locking adhesive, so that the frequency of disassembly can be matched to the locking capability of the adhesive. For example, Loctite 242 is for removable fasteners, and Loctite 2719 is for tamper-proof fasteners. Other manufacturers also make similar products. Most of these adhesives work in one of two ways. They are either a single mixture that hardens when it becomes a thin layer in the absence of air or an epoxy in two layers that does not harden until it is mixed and compressed between the mating threads. Note that the two-layer adhesives are usually put on the fastener as a "ribbon" or ring by the manufacturer. These ribbons or rings do have some shelf life, as long as they are not inadvertently mixed or damaged. These adhesives are usually effective as thread sealers as well. However, none of them will take high temperatures. The best adhesives will function at 450°F; the worst only at up to 200°F.

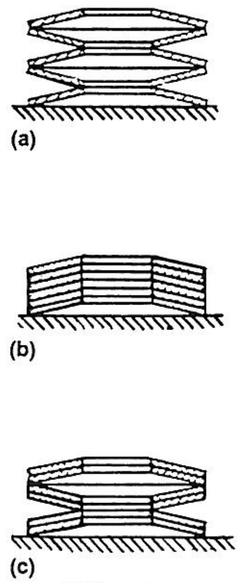
Washers

Belleville Washers: Belleville washers (Figure 12) are conical washers used more for maintaining a uniform tension load on a bolt than for locking. If they are not completely flattened out, they serve as a spring in the bolt joint. However, unless they have serrated surfaces, they have no significant locking capability. These surfaces, on the other hand, will damage the mating surfaces under them. These washers can be stacked in combinations as shown in Figure 13 to either increase the total spring length (Figure 13(a) and (c)) or increase the spring constant (Figure 13(b)).



(a) Smooth.
(b) Serrated.

Figure 12.—Types of Belleville washers.



(a) In series.
(b) In parallel.
(c) In-parallel series.

Figure 13.—Combinations of Belleville washers.

Lockwashers: The typical helical spring washer shown in Figure 14 is made of slightly trapezoidal wire formed into a helix of one coil so that the free height is approximately twice the thickness of the washer cross section. Lockwashers are usually made of hardened carbon steel, but they are also available in aluminum, silicon, bronze, phosphor-bronze alloy, stainless steel, and K-Monel. The lockwasher serves as a spring while the bolt is being tightened. However, the washer is normally flat when the bolt is fully torqued. At this time it is equivalent to a solid flat washer, and its locking ability is nonexistent. In summary, a lockwasher of this type is ineffective as a locking mechanism.

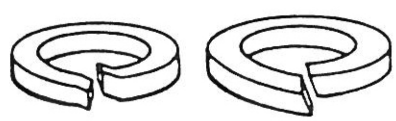
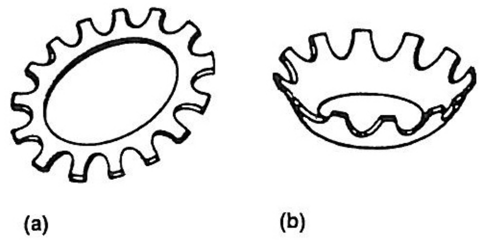


Figure 14.—Helical spring washers.

Tooth (or Star) Lockwashers: Tooth lockwashers (Figure 15) are used with screws and nuts for some spring action but mostly for locking action. The teeth are formed in a twisted configuration with sharp edges. One edge bites into the bolt head (or nut) while the other edge bites into the mating surface. Although this washer does provide some locking action, it damages the mating surfaces. These scratches can cause crack formation in highly stressed fasteners, in mating parts, or both, as well as decreased corrosion resistance.

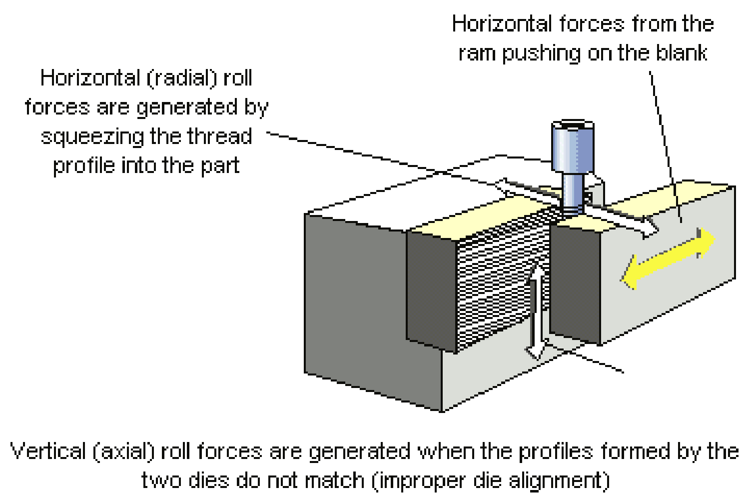


(a) Flat.
(b) Countersunk.
Figure 15.—Tooth lockwashers.

Inserts: An insert is a special type of device that is threaded on inside diameter and locked with threads or protrusions on outside diameter in a drilled, molded, or tapped hole. It is used to provide a strong, wear-resistant tapped hole in a soft material (e.g. plastics, nonferrous metals), as well as to repair stripped threads in a tapped hole. The aerospace industry uses inserts in tapped holes in soft materials in order to take advantage of weight savings provided by small high-strength fasteners. The bigger external thread of the insert (nominally 1/8 in. bigger in diameter than the internal thread) gives, for example, a 10-32 bolt in an equivalent 5/16-18 nut. In general, there are two types of inserts: those that are threaded externally, and those that are locked by some method other than threads (knurls, serrated surfaces, grooves, or interference fit). Within the threaded inserts there are three types: the wire thread, the self-tapping, and the solid bushing.

Forming of Threads

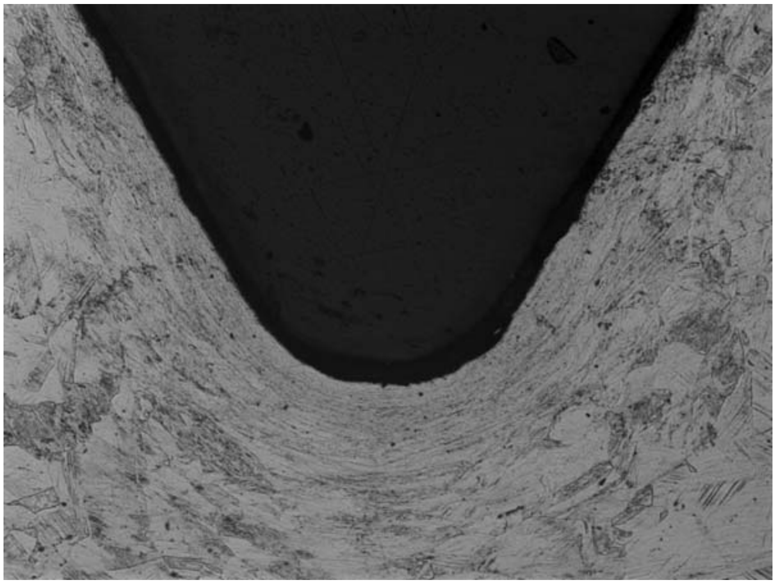
Threads may be cut, ground, hot rolled, or cold rolled. The most common manufacturing method is to cold form both the head and the threads for bolts up to one inch in diameter. In this process the threads are formed by rolling a thread blank between hardened dies that cause the metal to flow radially into the desired shape. Because no metal is removed in the form of chips, less material is required, resulting in substantial savings. Additionally, because of cold working, the threads have greater strength than cut threads, and a smoother, harder and more wear resistant surface is obtained. Cold rolling increases the strength of the bolt threads through the high compressive surface stresses, similar to the effects of shot peening. This process makes the threads more resistant to fatigue cracking. Furthermore, the process is automated and fast, with production rates of one per second being common. Thread rolling is done by several methods. The simplest one employs one fixed one movable flat die as shown below. After the blank is placed in position on the stationary die, movement of the moving die causes the blank to be rolled between the two dies and the metal in the blank is displaced to form the threads. The other most common method is done with cylindrical dies. The photo below illustrates the three-roll method commonly employed. With this procedure the inner most 1.5 to 2 threads are not formed to full depth because of the progressive action of the rollers.



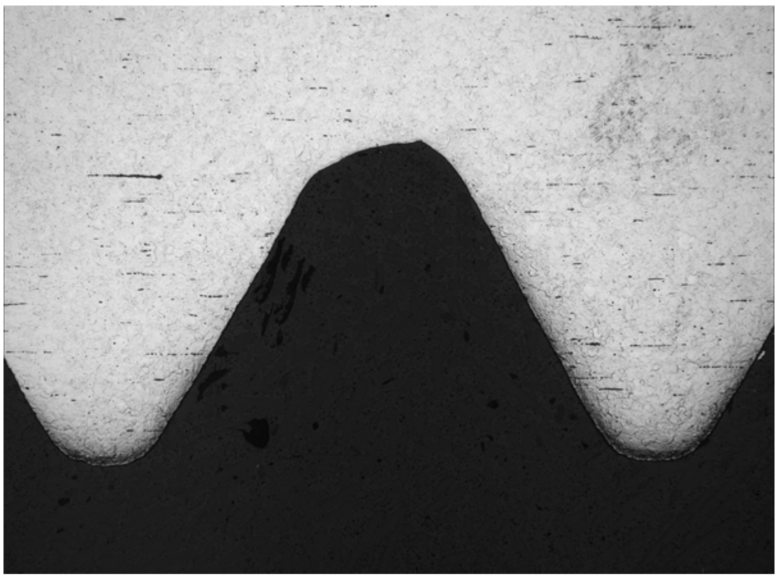
One obvious characteristic of a rolled thread is that its major diameter always is greater than the diameter of the blank. When an accurate class of fit is desired, the diameter of the blank is made about 0.002 in. larger than the thread pitch diameter. If it is desired to have the body (shank) of the bolt larger than the outside diameter of the rolled thread, the blank for the thread is made smaller than the body.

For bolts of larger diameter and high-strength smaller bolts, the heads are hot forged. The threads are still cold rolled until the bolt size prohibits the material displacement necessary to form the threads (up to a constant pitch of eight threads per inch). Threads are cut only at assembly with taps and dies or by lathe cutting.

The grain structures of the rolled versus the cut threads are illustrated below where the grain flow around the thread is evident, which makes the thread area stronger.



Micrograph showing rolled threads



Micrograph showing cut threads

Classes of Threads

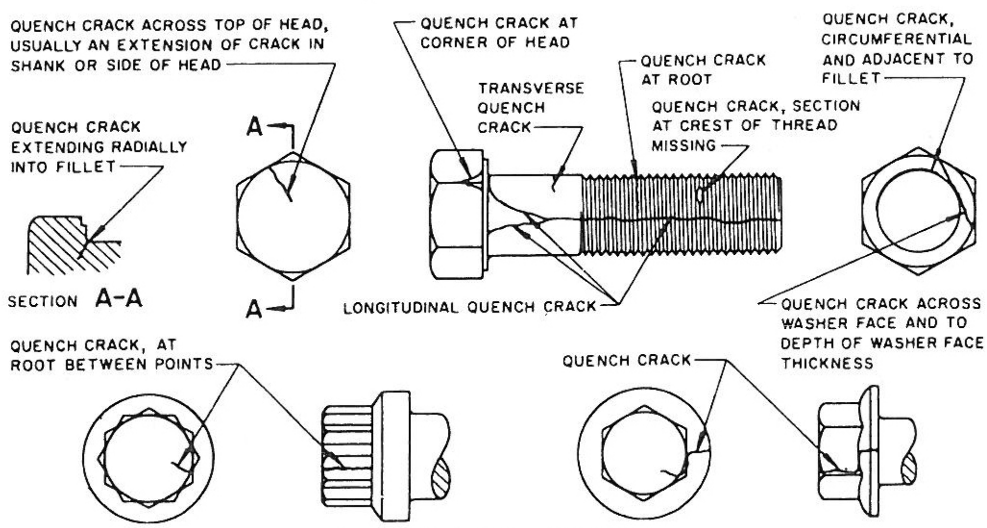
Thread classes are distinguished from each other by the amounts of tolerance and allowance. The designations run from IA to 3A and IB to 3B for external and internal threads, respectively. A class I is a looser fitting, general-purpose thread; a class 3 is the aerospace standard thread, and has a tighter tolerance. The individual tolerances and sizes for the various classes are given in the SAE Handbook.

Surface Discontinuities

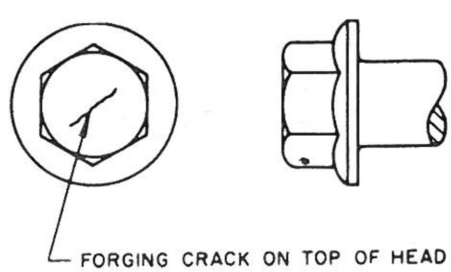
Various types of discontinuities may occur during the manufacture and processing of fasteners. Some are critical and render the fastener unusable, others are considered acceptable. In rolled threads, laps have been accepted in all but critical applications (aerospace, nuclear, medical, etc.)

as a normal side effect of a high-speed production process. The secret of flaw free threads lies in the geometry of the dies and their ability to control the flow of displaced material during the rolling process. This minimizes the tendency of the blank to skid.

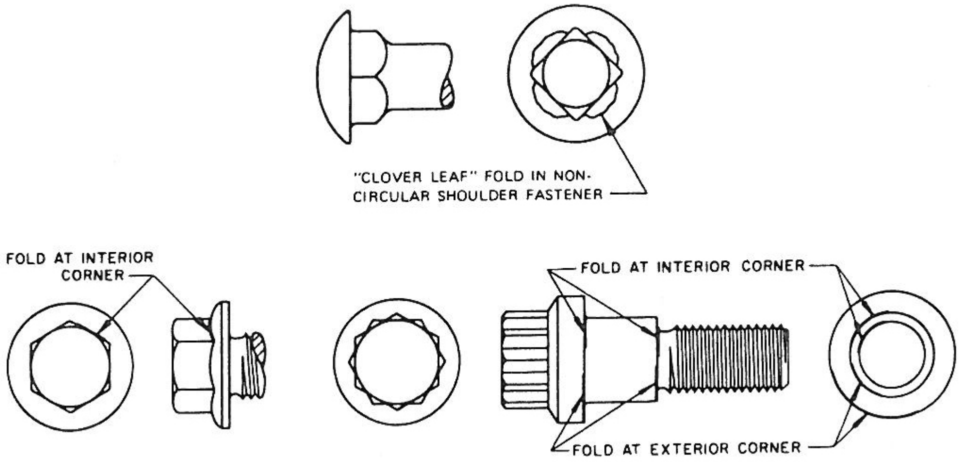
Quench cracks occur during heat treatment due to excessively high thermal stresses when process parameters are not controlled adequately, forging cracks, folds and bursts during forging operations. Seams are generally inherent in the raw material and are usually straight and smooth – curved linear discontinuities running longitudinally on bolts. Voids are shallow pockets on the surface due to nonfilling of metal during forging or upsetting. Tool marks are longitudinal or circumferential grooves of shallow depth produced by the manufacturing tools over the surface. Cracks of any kind are not allowable in fasteners. Bursts and seams are permitted up to certain size and depth. Folds are also acceptable unless they are at high stress areas such as the head-to- shank juncture. Laps formed in the threads during the rolling process also have some acceptable limits but have to be evaluated metallurgically through destructive tests and microscopic evaluations. These various defect types are illustrated in below figures.



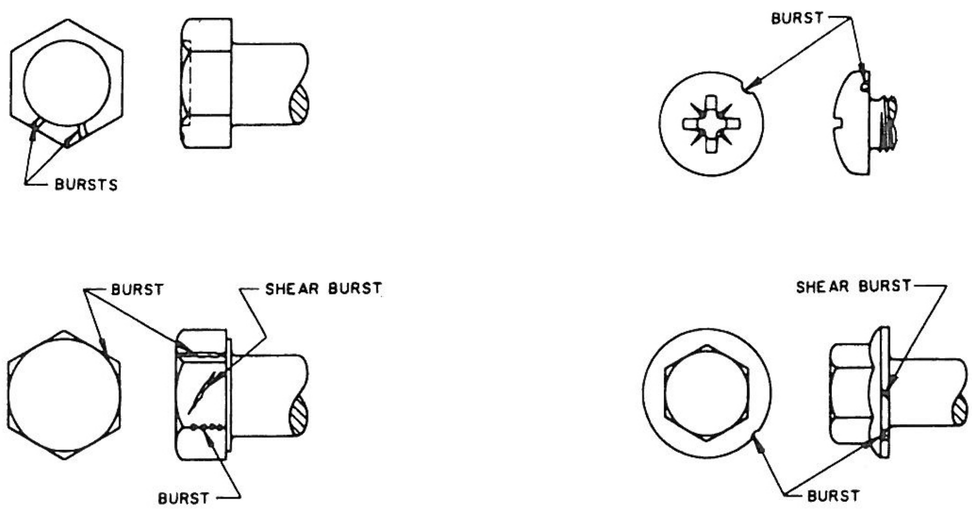
Typical Quench Cracks



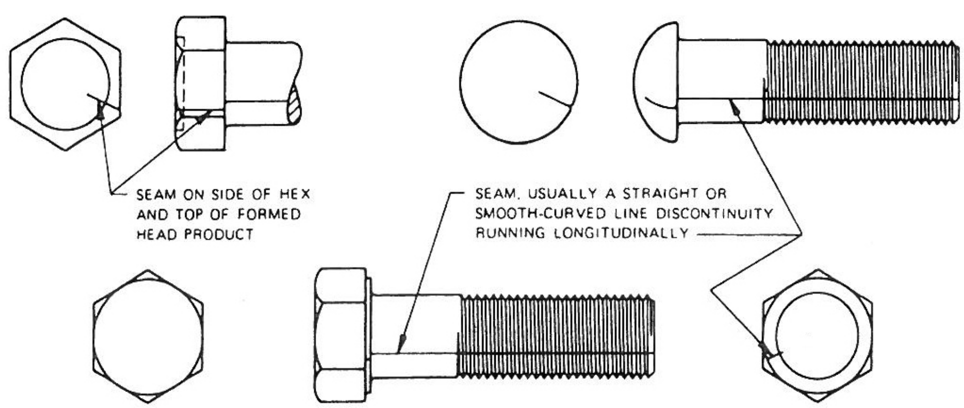
Typical Forging Cracks



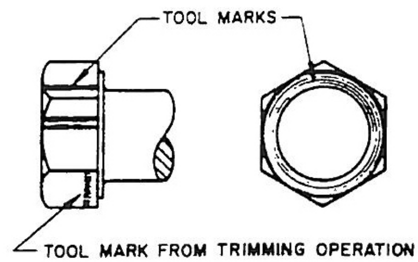
Typical Folds



Typical Bursts and Shear Bursts

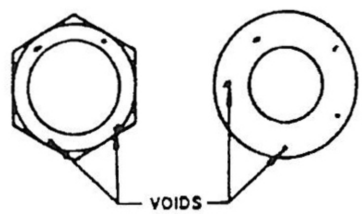


Typical Seams



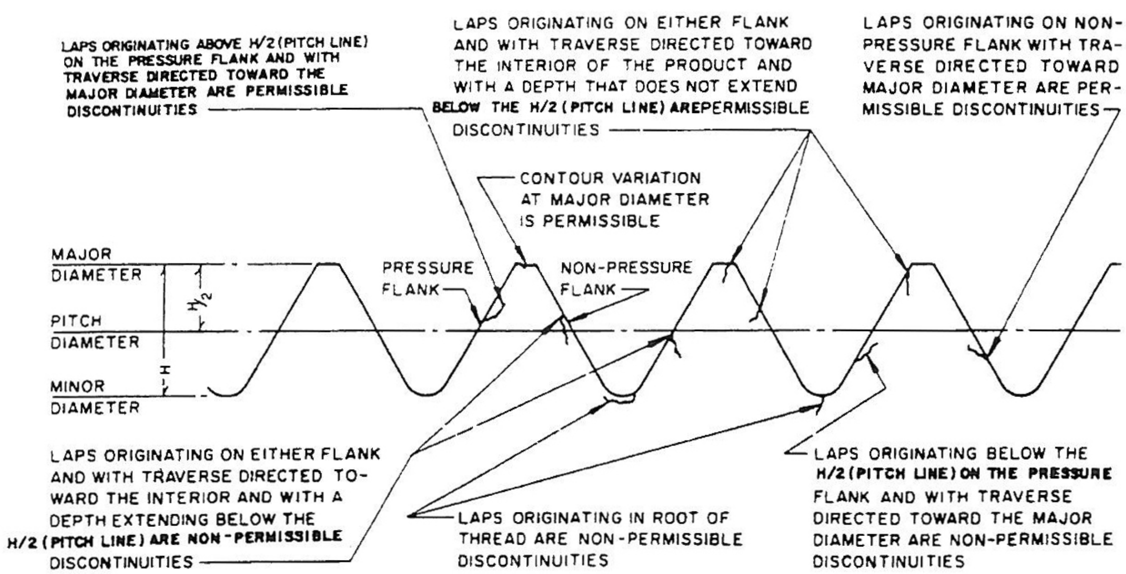
NOTE—Tool marks are permissible discontinuities if within the limits specified

TYPICAL TOOL MARKS



NOTE—Voids are permissible discontinuities if within the limits specified

TYPICAL VOIDS ON BEARING SURFACE

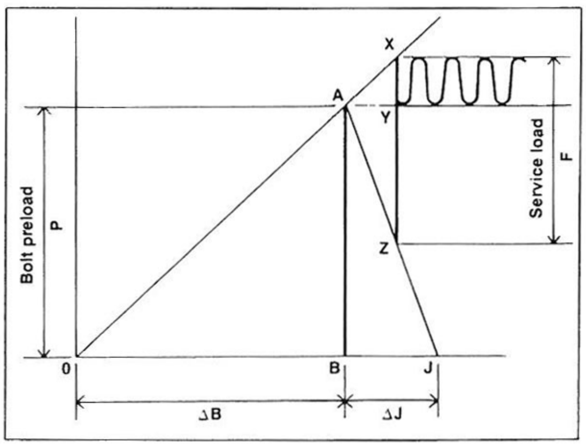


NOTE—These requirements apply to all bolts and screws except tapping screws with spaced threads.

SURFACE DISCONTINUITIES IN EXTERNAL SCREW THREADS

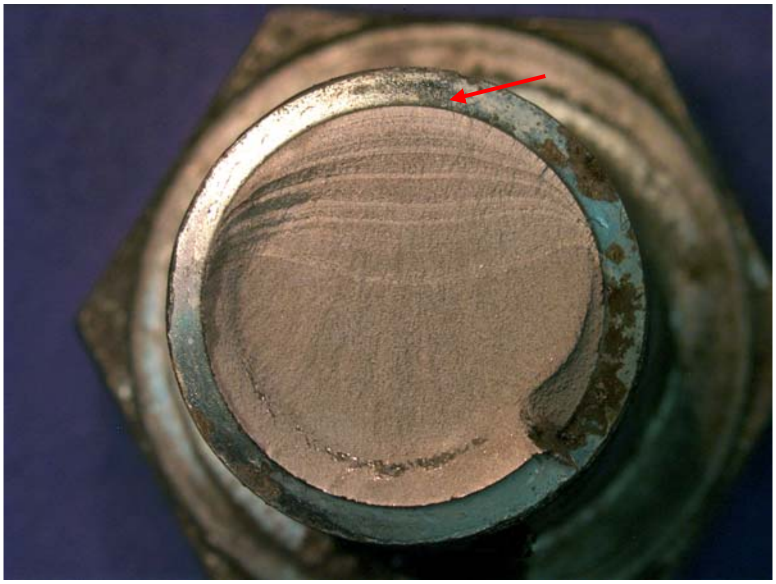
Fatigue

Over half of the industrial fastener failures are caused by fatigue. When a material is subjected to an alternating tensile stress, it will fracture at a load below its static tensile strength. The actual level depends on the number of load cycles. Fatigue life is the number of loading cycles a material can survive when stressed at a given load. The higher the load, the shorter the life. The load level where the life becomes infinite is called the endurance limit. Bolts have one of the worst geometrical shapes for resisting fatigue. Their stress concentration points, head-to-shank junction and threads, significantly reduce their fatigue properties compared to the material they are made from. As an example, a bolt made out of a material having 125,000 psi tensile strength may only have 25,000 psi endurance limit.
What happens in a joint subjected to dynamic and alternating service loads is best explained by examining the joint diagram below where the service load (F) fluctuates.

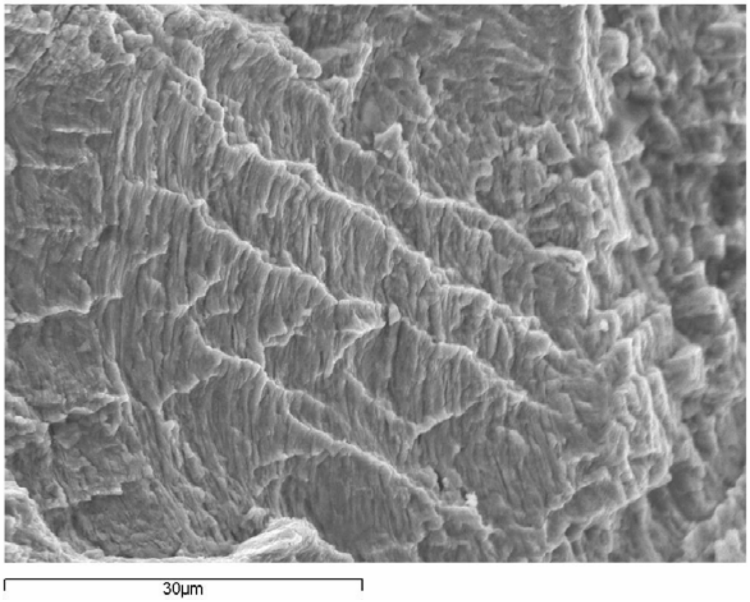


Joint diagram — alternating service load.

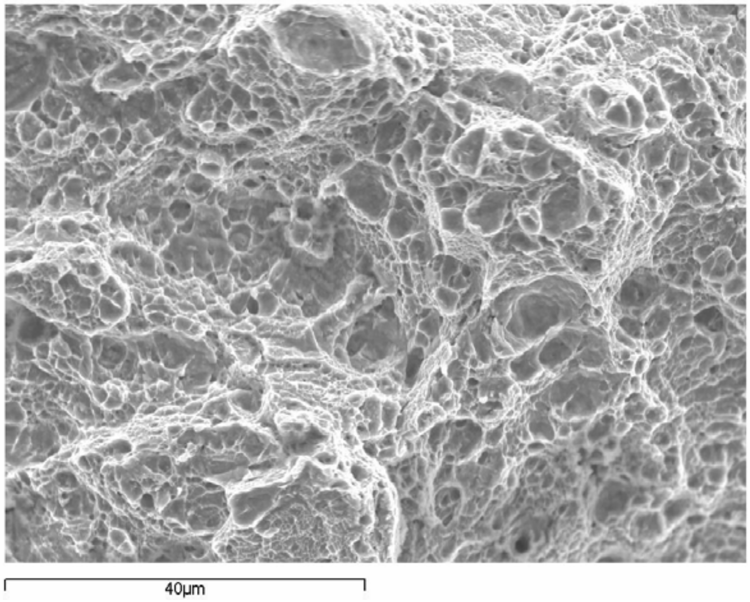
The portion of F adding tension into the bolt is XY which is now cyclic, alternating the stress in the bolt between preload and preload plus XY. Extensive research has demonstrated that a bolt's basic fatigue properties remain essentially unchanged regardless of the level of initial preload. Consequently, the fatigue life of the bolt in the joint depends on the magnitude of the alternating service load, the bolt's share of this load and the number of load applications. The best situation is when the share of the service load felt by the bolt is less than the bolt's endurance limit, in which case the bolt survives indefinitely. The worst case occurs when the preload is too low, the preload is lost (i.e. bolt has loosened), or service loads are excessive and the joint separates. When separation occurs the bolt assumes the full load and early failure becomes imminent. Fatigue failures generally show little evidence of deformation. Because of this lack of deformation, fatigue cracks are difficult to detect until substantial crack growth has occurred. A fatigue fracture surface normally presents a characteristic appearance, with distinct regions. The first region corresponds to slow stable crack growth. This usually exhibits a smooth surface. Second region is typically rougher in texture as the distance and rate of crack growth from the initiation site increases. The third region is the final overload fracture, which may be either ductile or brittle depending on the circumstances. Below figures illustrate some of these features.



Macrophotograph showing the fracture surface
Arrow points to the fatigue initiation site



Scanning electron micrograph showing fatigue striations, which indicate progressive crack growth occurring with each load cycle that is above a critical stress level



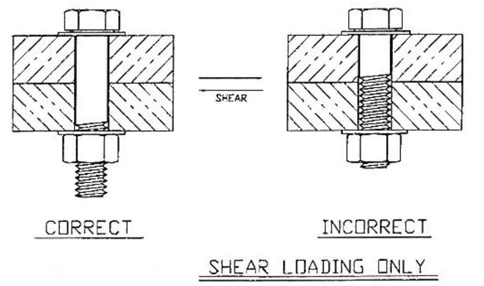
Scanning electron micrograph showing ductile fracture features in the final separation region

Fatigue-Resistant Bolts: If a bolt is cycled in tension, it will normally break near the end of the threaded portion because this is the area of maximum stress concentration. In order to lessen the stress concentration factor, the bolt shank can be machined down to the root diameter of the threads. Then it will survive tensile cyclic loading much longer than a standard bolt with the shank diameter equal to the thread outside diameter. Another way of guarding against fatigue is to use fasteners with forged heads, which precludes the planes of weakness caused by machining. A smooth fillet design to blend the sharp radius profile where the head meets the shank also decreases the possibility of fatigue crack initiation.

Shear Loading

The most common of all joints-particularly structural steel connections- are those in which the loading direction of the primary service loads are perpendicular to the axes of the connecting fasteners (splices). Such loadings induce transverse shear in the bolts rather than stretching them in tension. When bolts are tightened to low preload levels, joints may slip bringing the bolts into bearing and shear. The load carrying capacity then becomes the number of bolts multiplied by the number of shear planes multiplied by bolt shear strength. The bolt shear strength is the product of its cross sectional area multiplied by ultimate shear stress. Shear planes cut through the unthreaded shank or through threads. Shear stress through unthreaded shanks is computed using nominal bolt size, and shear areas through the threads are computed using the thread minor diameter. If the bolt is loaded in shear through the threaded area, the stress level is higher. Therefore, shear loads should be carried on the unthreaded shank, not in the threaded area. Correct way of installing a fastener that will be subjected to shear is illustrated below.

For the structural sizes of coarse thread inch and metric bolts, thread root areas are about 70 percent of full body areas. Ultimate shear strength of carbon steel approximates to 60 percent of its ultimate tensile strength.



When bolts are preloaded the joint members are clamped tightly together and cannot move transversely relative to each other until the frictional resistance between their contacting surfaces is exceeded. Until that happens, the bolt is only stressed by its preload. Frictional resistance equals total clamping load -preload of all bolts- multiplied by the number of contacting surfaces, multiplied by their coefficient of friction. If the frictional resistance is lower than the externally applied load then the joint slips and the bolts are subjected to both shear and tensile loads.

Vibration

Vibration is the enemy of fasteners. It causes loosening, which almost always leads to failures. Fasteners in statically loaded joints don't loosen. However in any joint that experiences dynamic loads, stress reversals or vibration, fasteners are susceptible to loosening. In tightened fasteners, the axial tensile stress develops frictional resistance between bolt and nut surfaces bearing against the joined material. If this frictional resistance is reduced, the same tensile strength in the bolt now encourages the mating threads to "walk" due to the downhill slope of their helix angle. Any motion reduces bolt preload and progressively, over a number of pulsations, the motion continues until preload is completely lost and the joint separates. The best way to ensure against loosening is to clamp the joined material together so tightly that the magnitude of the developed frictional resistance significantly exceeds that of any transversely applied service load. This means high bolt preload and more important, retention of sufficient residual preload following any long-term relaxation the joint may experience after it enters service. Relaxation occurs due to several reasons. Rough spots on contacting surfaces flatten, mating threads accommodate to each other, there may be embedment of bolt head and nut into the joined material, and the fasteners adjust to nonparallel bearing surfaces. Using hardened washers under bolt heads and nuts to distribute bearing stresses, adding bolt length to improve their elasticity and permit greater elongation when preloaded, and retightening after a few hours or days are some of the ways to minimize joint relaxation. Furthermore, some measures worth considering to prevent loosening are:
Use of fasteners with length-to-diameter ratios of 8:1 and higher, use of jam nuts, slotted nuts with cotter pins, and lock wires laced through drilled bolt heads, tack welding joint members (as long as welding heat cannot negatively affect fastener properties), use of prevailing-torque fasteners. Prevailing-torque fasteners are fasteners with the same strength capabilities as their "standard" counterparts, but they have an additional designed-in ability to resist removal motion when assembled with a mating thread. The two basic designs are those with deformed threads and those with a non-metallic ring, plug or strip added into their thread mating length. These features help dampen high frequency resonance which may be induced in the fastener by low-frequency vibration or random impacts. Also, the prevailing torque feature keeps the nut from falling completely off the bolt if preload is lost.

Thermal Cyclic Loading of Bolts

If the bolt and joint are of different materials, an operating temperature higher or lower than the installation temperature can cause problems. Differential contraction between joint members and bolts can cause the joint to unload (i.e. separate); differential expansion can also cause overloading of the fasteners. In these cases it is common practice to use conical washers to give additional adjustments in fastener and joint loading.