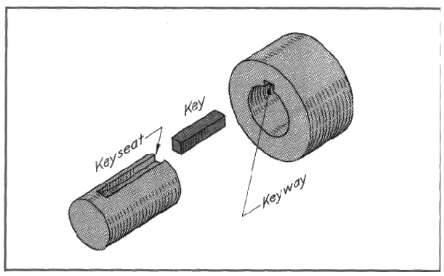
KEYS

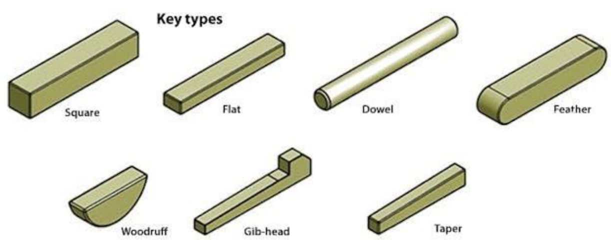
Keys are used on shafts to enable torque transmission from the shaft to attached elements like gears and pulleys. They prevent axial movement and help in torque or thrust transfer. Keys are typically more suited for transmitting torque, while pins are mainly for positioning or securing, especially where shear forces are involved.

Keyseat

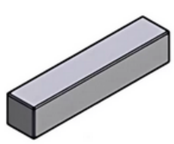
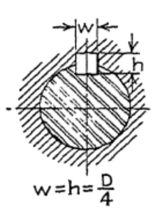
	A keyseat is a groove on the shaft where the key sits. Proper design minimizes stress concentration. Stress concentrations in keyseats vary by shape; sled-runner keyseats reduce abrupt edges to lower stress. Key material should typically be low-carbon steel to prevent premature wear.

Shaft keys (Video) are small machine members inserted between a shaft and a hub to prevent angular rotation. Keys require a key seat both in the shaft and the hub. Keys also act like a fuse, in which it is designed to fail first before the shaft is damaged completely.

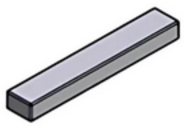
Different types include square keys, gib-head keys, and Woodruff keys, each designed for specific applications, load types, and stress distribution.

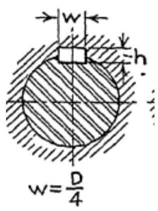


1. Square Key

 	A square key is a critical power transmission component with a uniform square cross-section, meaning its width and height are equal. It fits snugly into matching rectangular keyways on both a shaft and a hub, such as a pulley or gear, to prevent relative rotation and ensure robust torque transmission. Due to its simple geometry, it is easy to manufacture, cost-effective, and ideal for general industrial applications involving moderate to high torque. Square Key are unsuitable for high-speed applications where precise alignment is required to prevent vibration. Additionally, the sharp corners of the keyway can create stress concentrations, making them less ideal for systems experiencing severe shock loads. Despite these drawbacks, the square key remains a standard choice for basic mechanical assemblies due to its reliability and ease of installation.

2. Flat Key





A flat key is a mechanical coupling similar to a square key, but it features a reduced height relative to its width, resulting in a distinct rectangular cross-section. This low-profile design allows it to fit into shallower keyways, making it an ideal choice for applications where radial space is limited or where the shaft diameter is relatively small. It is most commonly used in setups that bear loads in a single direction or for transmitting lighter torque compared to its square counterpart.

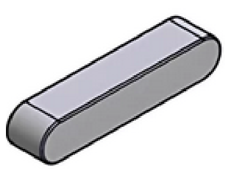
The primary advantage of the flat key is its compact nature, which facilitates easier installation in tight mechanical assemblies. However, because of its thinner profile, it possesses a lower shear area vertically, meaning it cannot handle the same high-torque intensity as a square key. Despite this limitation, it remains a highly efficient and space-saving solution for standard industrial components like small pulleys, fans, and light-duty pumps.

3. Dowel Key

A dowel key, also frequently referred to as a pin key or round key, is a cylindrical, pin-like fastener designed to fit into a matching round groove or hole drilled into both the shaft and the hub. Unlike square or flat keys that rely on rectangular slots, the dowel key utilizes a circular geometry that allows it to act as both a torque transmitter and a high-precision locating element. It is most commonly employed in coupling applications and machinery where maintaining the exact axial and radial alignment of components is critical for operation.

The primary advantage of the dowel key is its ability to provide superior alignment and its extreme simplicity in terms of manufacturing and installation, as it often only requires a standard drilling and reaming process. However, its main limitation is its lower torque-transmitting capacity compared to square keys, as the circular cross-section offers less surface area to resist shearing forces. Consequently, it is best suited for light-to-moderate loads or as a secondary security measure in precision assemblies.

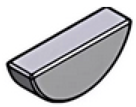
4. Feather Key

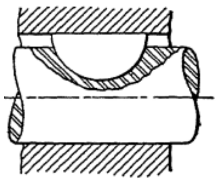


A feather key is a specialized mechanical fastener designed to transmit torque between a shaft and a hub while uniquely allowing for relative axial movement (sliding) along the shaft's length. Typically shaped as a parallel key, it often features rounded or "dog-point" ends to minimize stress concentrations and facilitate smoother sliding. Unlike standard keys that lock a component in a fixed position, the feather key is tightly secured—usually by screws—to either the shaft or the hub, ensuring it remains in place while the mating part slides over it.

This type of key is essential in applications such as sliding couplings, gear shifting mechanisms, or machines requiring frequent axial adjustments during operation. Its primary advantage is maintaining a constant torque-transmitting connection without hindering axial travel. However, it is not suitable for applications that require a permanently fixed axial position, as the design is inherently intended to facilitate movement. Its reliability makes it a staple in complex drivetrain systems where components must reposition under load.

5. Woodruff Key

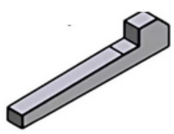


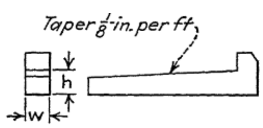


A Woodruff key is a specialized, semi-circular fastener designed to fit into a matching milled, semi-circular keyseat in a shaft. Its unique rounded geometry allows the key to pivot slightly within its seat, a feature that ensures the key automatically aligns itself with the hub's keyway during assembly. This self-aligning capability makes it exceptionally easy to install and significantly less prone to tilting or slipping compared to standard parallel keys.

Woodruff keys are commonly found in automotive engines, machine tools, and light-duty power transmission systems where precise alignment is more critical than high-load capacity. However, a major limitation of this design is that it requires a significantly deeper keyseat than square or flat keys. This deep cut can substantially weaken the shaft's cross-sectional strength, making it less suitable for high-torque applications. Despite this, its reliability in maintaining alignment under small-to-moderate loads makes it a staple in precision mechanical engineering.

6. Gib-Head Key

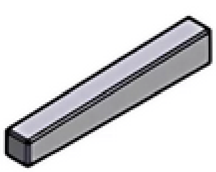


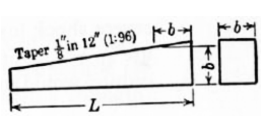


A Gib-head key is a specialized variation of a tapered machine key, distinguished by a prominent, protruding head on its larger end. This unique "gib head" is specifically designed to facilitate easy removal; it provides a surface that can be gripped or struck with a wedge or hammer, allowing the key to be extracted even from a tight, seated position without damaging the shaft or the hub. The body of the key is tapered along its length, which ensures a powerful, wedge-like friction fit that securely locks the components together and prevents both rotational and axial movement.

This type of key is commonly used in heavy machinery and industrial equipment where frequent disassembly for maintenance or repair is required. While its primary advantage is the ease of extraction and a highly secure fit, it does have limitations. The protruding head can be a safety hazard if left exposed on a rotating shaft, and the tapered design requires precise machining of the keyway to ensure the angles match perfectly for maximum contact.

7. Taper Key



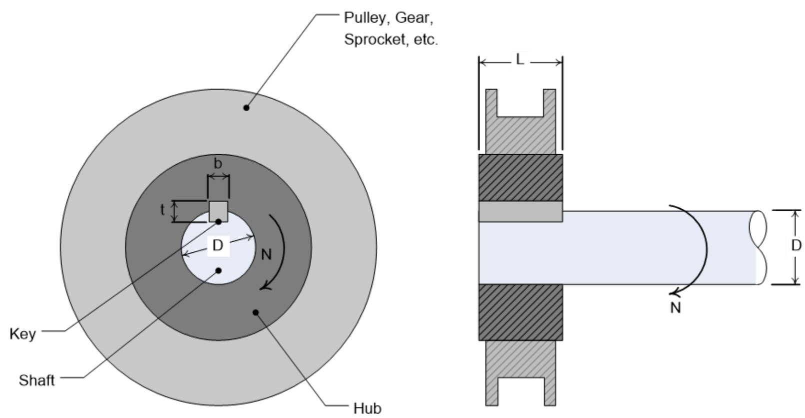


A tapered key is a robust mechanical fastener characterized by a slight, uniform decrease in height along its longitudinal axis, typically following a standard gradient such as 1 in 100. Unlike parallel keys that rely primarily on side-wall pressure, the tapered key is designed to be driven forcefully into the keyway, creating a powerful frictional grip and a wedge-like compressive force between the shaft and the hub. This unique loading mechanism not only prevents relative rotation but also provides axial locking, making it indispensable for heavy-duty applications such as flywheels, large industrial gears, and heavy pulleys where a secure, non-slip fit is essential.

The primary advantage of this design is the high integrity of the connection, which remains tight even under fluctuating loads; additionally, it can be easily removed by tapping it out from the smaller end. However, a significant limitation is that the wedging action can induce high radial stresses, potentially leading to stress concentrations or even cracking in the shaft or hub if not properly accounted for in the design phase.

Importance of Keys:

- Torque Transmission: Keys ensure that rotational torque is transmitted from the shaft to the connected mechanical element, like a gear or pulley, without slipping.
- Damage Prevention: Keys often act as sacrificial components. They are designed to fail before the shaft or hub is damaged in case of an overload, thereby protecting the more expensive parts of the system.
- Easy Assembly/Disassembly: Keys allow for the secure connection and easy removal of mechanical components from shafts, simplifying maintenance, repair, and assembly of machinery.



Where: D = shaft diameter
L = length of the key = length of the hub = 1.5D
t = thickness of the key
b = width of the key

Note: Hub and the pulley are made of the same material
b > t
size of the key: b x t x L

Power Transmitted by the key:

$$P = \frac{2\pi TN}{60}$$

Where: P = power transmitted, kW
T = torque or torsional moment
N = speed (rpm)

Torque Transmitted:

$$T = (F)(r)$$

$$T = F\left(\frac{D}{2}\right)$$

Note: Torque capacity for one key = total torque transmitted
$T_k = T$

Design of keys:

1. Based on torsional stress in the shaft

$S_s = \frac{16T}{\pi D^3}$ pure torsion of a solid shaft

Most materials are tested in tension (pulling), but shafts and keys fail in shear (cutting). According to the **Distortion Energy Theory (Von Mises)** (Refer to page 236: Design of Machine Elements 4th Edition by Virgil Faires), a material will yield in shear at approximately 57.7% (often rounded to **60% or 0.6**) of its tensile limit.

$$S_s = 0.60\, S_y$$

$$0.60\, S_y = \frac{16T}{\pi D^3}$$

(Refer to the statement from Table AT 7, page 576: Design of Machine Elements 4th Edition by Virgil Faires). The 0.60 factor is an industry-standard approximation used in design to estimate shear yield strength from tensile yield strength for ductile materials.

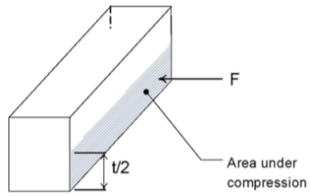
The **Factor of Safety** is an engineering margin added to account for uncertainties, such as: Unexpected shock loads or vibrations, Material defects or manufacturing tolerances and Wear and tear over time. Considering the Factor of Safety, FS = $\frac{S_{fail}}{S_{all}}$ we will have:

$\frac{0.60\, S_y}{FS} = \frac{16T}{\pi D^3}$ Design Equation for Solid Shafts (considering Shear Yield and Safety Factor)

Factor of safety (Design Factors)

F.S. = 1.5	for smooth loading
F.S. = 2.0 – 2.25	for minor shock loading
F.S. = 4.5	for severe shock loading

2. Based on the compressive stress between the key/hub or key/shaft



$S_c = \frac{F}{A}$

Then: $F = \frac{2T}{D}$ and $A = \frac{t}{2}L$ substituting,

$S_c = \frac{4T}{DtL}$

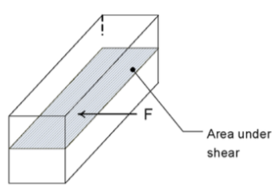
We don't use 0.60 in compression because for ductile steels, the strength in Compression (Crushing) is considered equal to its strength in Tension, so we use the full Yield Strength (S_y) as our basis, or $S_c = S_y$.

For the design compressive stress:

$S_c = \frac{S_y}{FS}$

Considering safety, always use the yield strength (S_y) of the weakest material—whether it is the key, the hub, or the shaft—to ensure that no part of the joint crushes under pressure.

3. Based on shearing of the key



$S_s = \frac{F}{A}$

Then: $F = \frac{2T}{D}$ and $A = bL$ substituting,

$S_s = \frac{2T}{DbL}$

For the design shearing stress:

$$0.60\,S_y = \frac{2T}{DbL}$$

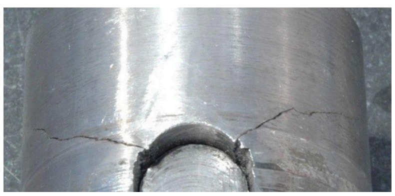
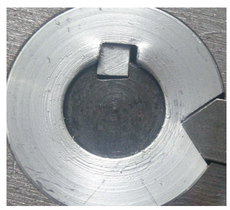
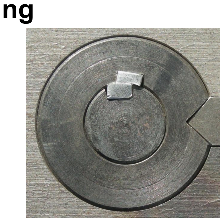
S_y = yield stress based on the material of the key

Considering the Factor of Safety, FS = $\frac{S_{fail}}{S_{all}}$ we will have;

$$\frac{0.60\,S_y}{FS} = \frac{2T}{DbL}$$

Design Equation for Solid Shafts (considering Shear Yield and Safety Factor)

Failures of Keys

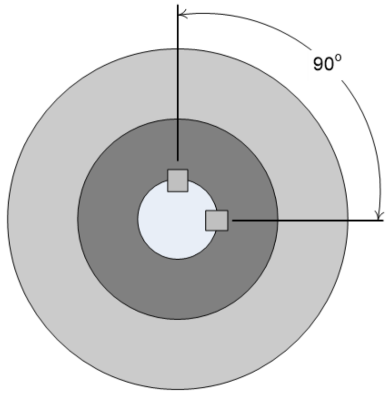
Torsion	**Compression**	**Shearing**
 Affects the shaft, not the key itself. It's considered when calculating the shaft's capability to transmit torque, but not the primary failure mode of the key.	 Arises due to contact pressure between the key and the keyway surfaces. It's also important but usually less critical than shear because materials generally have higher compressive strength than shear strength.	 Occurs between the key and shaft/hub interface. It is directly responsible for torque transmission and often governs the torque capacity of the key. Shearing stress contributes the most to the failure of keys.

Keys are often designed based on their shear strength, and shear failure is common when overloaded.

Number of Keys Used:

For heavy loads, two or more keys can be employed. Two keys are usually separated by 90 degrees and each key can be sized to carry 20 percent more than one-half of the total torque. Three keys are usually separated by 120 degrees and each key can carry 15 percent of the total torque.

Design of 2-keys separated by 90°



1. Torque Transmitted per key: $T_k = 1.2\frac{Total\ torque\ transmitted}{number\ of\ keys} = 1.2\frac{T}{N_k}$

   Where: N_k = number of keys

   The factor 1.2 in the equation represents a safety factor or load distribution factor accounting for uneven torque distribution between the keys.

2. Based on the compressive stress between the key/hub or key/shaft

   From: $S_c = \frac{4T_k}{DtL}$ and $T_k = 1.2\frac{T}{N_k}$ substituting,

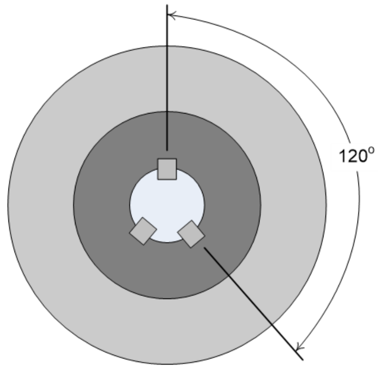
   $$S_c = 1.2\frac{4T}{DtLN_k}$$

3. Based on shearing of the key

   From: $S_s = \frac{2T_k}{DbL}$ and $T_k = 1.2\frac{T}{N_k}$ substituting,

   $$S_s = 1.2\frac{2T}{DbLN_k}$$

Design of 3-keys separated by 120°



4. Torque Transmitted per key: $T_k = 1.15 \frac{Total\ torque\ transmitted}{number\ of\ keys} = 1.15 \frac{T}{N_k}$

5. Based on the compressive stress between the key/hub or key/shaft

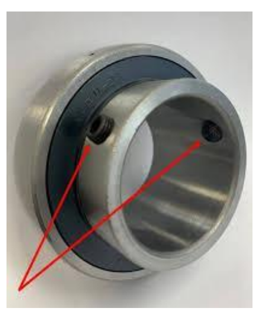
$$S_c = 1.15 \frac{4T}{DtLN_k}$$

6. Based on shearing of the key`

$$S_s = 1.15 \frac{2T}{DbLN_k}$$

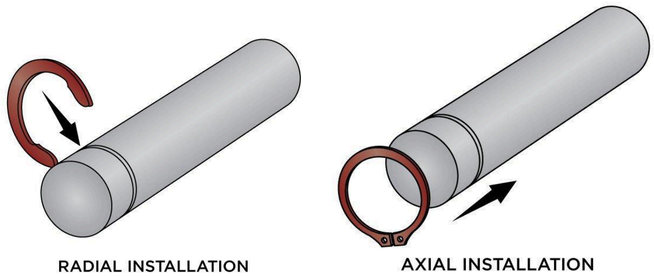
Other Miscellaneous Shaft Components

Setscrews



Unlike bolts, setscrews rely on compression rather than tension to provide clamping force.
They create holding power through frictional resistance between the collar and shaft, often aided by slight penetration into the shaft.
Typically, set screws should be around half the shaft's diameter in length and help secure the shaft radially.

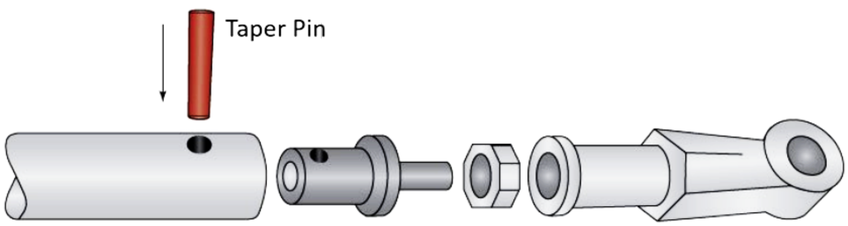
Retaining Rings



Retaining rings are an alternative to shoulders or sleeves for axial positioning on shafts. They fit into grooves in shafts or bores to hold components in place, especially under axial loads.

Special care should be taken with stress concentration factors, which are high due to the sharp groove radius, particularly under bending or torsion.

Taper Pin

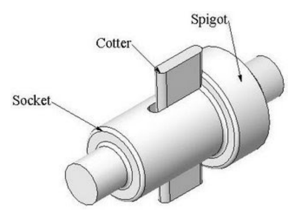
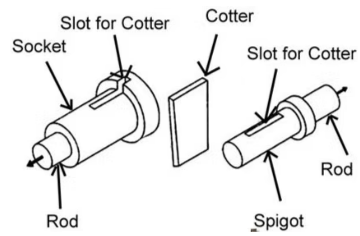


Standard taper pins are versatile mechanical fasteners primarily used for light-duty work to secure a hub to a shaft. They are typically installed either tangent to the shaft or directly through the diameter, as illustrated in technical figures where they effectively connect hollow shafts via a sleeve. The installation process is precise, requiring the pin holes to be drilled and then reamed with a specialized taper reamer only after the parts have been assembled to ensure a perfect, snug fit.

According to standard engineering proportions, the diameter of the large end of the pin should ideally be one-fourth of the shaft diameter to maintain structural integrity. These pins usually feature a standard taper of 1/4 inch per foot. Because of their tapered geometry, they provide a secure frictional grip that resists loosening due to vibration, yet they remain relatively easy to remove by driving them out from the smaller end, making them ideal for components requiring occasional disassembly.

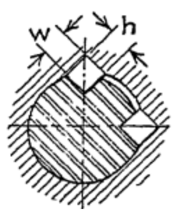
Cotter Joint

A cotter joint is a temporary mechanical fastening used to connect two co-axial rods subjected to axial tensile or compressive loads. Unlike a standard key, which transmits power through shear on an area parallel to its length, a cotter transmits power by shear on an area perpendicular to its length. The cotter itself is typically a flat, wedge-shaped metal bar that is tapered on one side; this taper is crucial as it ensures a tight, secure friction fit when driven into the assembly.

Commonly used in applications like long pump rods and similar machine members, cotter joints are designed to handle varying loads, including reversing stresses like tension and compression.

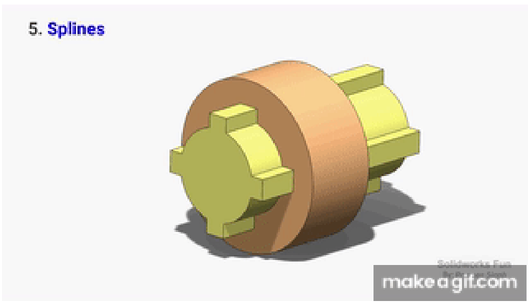
Kennedy Keys

	Kennedy keys (also referred to as tangential keys) are heavy-duty fastening components consisting of a pair of tapered square keys. They can be manufactured with or without gib heads to facilitate easier removal. These keys are unique because they are assembled such that their diagonal dimensions are positioned in a circumferential direction, allowing them to sit tangentially within the shaft and hub interface. Typically, two Kennedy keys are used together, spaced at a specific angle (usually 90◦ or 120◦), to provide a powerful wedge action. The primary advantage of this specific tangential configuration is a significant increase in torque-transmitting capacity compared to standard square or flat keys.

SPLINE SHAFT

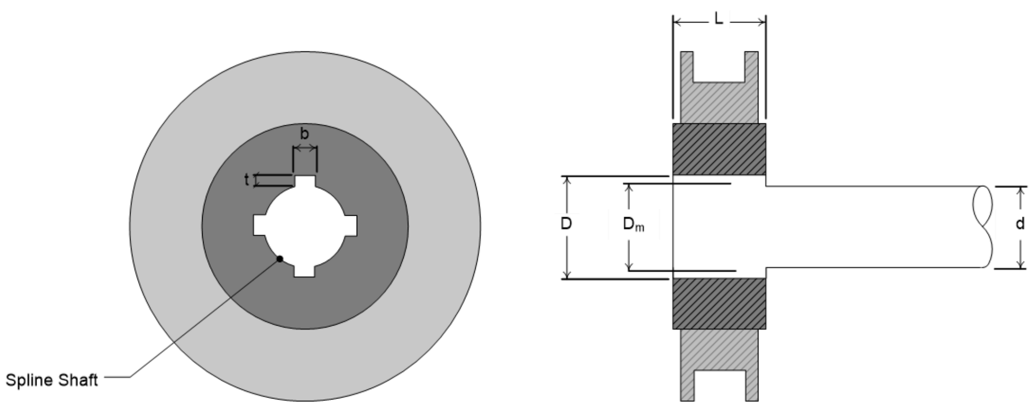
Splines are essentially gear-like teeth formed on the shaft and a matching component, used primarily for high torque transmission. They allow for a close fit between components, enabling relative movement while transmitting torque. Unlike keys, splines are more costly but provide a stronger connection without requiring additional securing elements. They are particularly useful in applications where large axial movement is needed, such as in power take-off (PTO) shafts on agricultural and industrial equipment. Stress concentrations at the ends of splines are moderate, but overall stress factors are generally low.

As a general industry standard, if torque requirements necessitate more than two or three individual keys, it is highly advisable to transition to a **splined shaft**. While it is technically possible to machine four or more keyways into a single shaft, doing so severely compromises the shaft's structural integrity. Each keyway acts as a significant stress raiser; multiple deep cuts create localized "weak spots" that can lead to fatigue failure. Splines, by contrast, are essentially "integral keys" machined directly into the shaft's periphery.



A spline shaft is a shaft with a series of permanent keys formed longitudinally around its circumference. Spline shaft is recommended when high torque capacity to be transmitted or when axial motion of the mating parts under load is expected.

Splines offer greater strength, torque capacity, and axial movement but are more costly, while keys provide a simpler, more affordable solution suited for moderate torque applications without axial movement needs.



Where: D = major diameter

D_m = mean diameter

d = shaft diameter

L = length of the spline = length of the hub = 1.5D

h = thickness of the spline

b = width of the spline

Note: Hub and the pulley are made of the same material
b>t
size of the spline: b x t x L

Power Transmitted by the key: $P = \frac{2\pi TN}{60}$

Torque Transmitted per spline: $T_s = 1.10 \frac{Total\ torque\ transmitted}{number\ of\ splines} = 1.10 \frac{T}{N_s}$

$$T = (F)\left(r_m\right)$$

$$T = F\left(\frac{D+d}{4}\right)$$

Note: r_m = mean radius

The factor 1.1 is known as the Load Distribution Factor, theoretically, if you have six splines, each tooth would carry exactly one-sixth of the load; however, because of machining inaccuracies, it is physically impossible to make every tooth identical. Tiny variations in thickness or spacing mean that some teeth will make contact before others, forcing them to carry more than their fair share of the torque. By applying the 1.1 factor, you are essentially adding a 10% "stress penalty" to your calculations, which acts as a safety buffer to ensure the shaft remains durable even if the load is distributed unevenly across the splines.
A factor of 1.0 represents a theoretical or perfect condition where every tooth shares the load equally—a scenario usually found only in ideal computer models.

Design of splines:

1. Based on torsional stress in the shaft

$S_s = \frac{16T}{\pi d^3}$ pure torsion of a solid shaft

Following the **Distortion Energy Theory (Von Mises),** a material will yield in shear at approximately 57.7% (often rounded to **60% or 0.6**) of its tensile limit.

$$S_s = 0.60\, S_y$$

$$0.60\, S_y = \frac{16T}{\pi d^3}$$

The **Factor of Safety** is an engineering margin added to account for uncertainties, such as: Unexpected shock loads or vibrations, Material defects or manufacturing tolerances and Wear and tear over time. Considering the Factor of Safety, FS = $\frac{S_{fail}}{S_{all}}$ we will have:

$$\frac{0.60\,S_y}{FS} = \frac{16T}{\pi d^3}$$ Design Equation for Splines (considering Shear Yield and Safety Factor)

S_y = yield stress based on shaft material

2. Based on the compressive stress between the spline/hub or spline/shaft

$$S_c = \frac{F}{A_c}$$

Where: $A_c = tL$ area under compression

From: $F = \frac{4T_s}{D + d}$ and $T_s = 1.1\frac{T}{N_s}$ substituting,

$$S_c = 1.1\frac{4T}{(D + d)tLN_s}$$

3. Based on shearing of the spline

$$S_s = \frac{F}{A_s}$$

Where: $A_s = bL$ area under shear

From: $F = \frac{2T_s}{d}$ and $T_s = 1.1\frac{T}{N_s}$ substituting,

$$S_s = 1.1\frac{2T}{dbLN_s}$$

For the design shearing stress:

$$S_s = \frac{0.60\,S_y}{FS}$$

S_y = yield stress based on the material of the spline

Stress Concentration in Splines:

- Splines experience stress due to torsional loads. Involute splines have lower stress concentration factors than parallel splines.
- Stress concentration factors vary based on fillet radius and spline profile design, with involute splines generally offering better performance.

Types of Fits:

Splines are categorized based on their intended mechanical behavior. **Permanent fits** are used for assemblies that do not require axial movement, whereas sliding fits are engineered for specific conditions. Some splines are designed to **slide when not under load** for easy repositioning, while others are precision-machined to s**lide while under load**, such as those found in automotive transmissions or PTO shafts. The use of an involute profile (similar to gear teeth) has become the modern standard because these splines are self-centering, provide maximum strength at the base of the tooth, and can be manufactured using standard gear-cutting techniques like hobbing or broaching.

NOMINAL DIMENSIONS OF SPLINES

NO. OF SPLINES	STANDARD SIZES, NOMINAL	ALL FITS	PERMANENT FIT		NOT SLIDE UNDER LOAD		SLIDE UNDER LOAD	
		b	t	d	t	d	t	d
4	by 1/8-in. from 3/4 in. to 1 3/4; 2, 2 1/4, 2 1/2, 3	0.241D	0.075D	0.850D	0.125D	0.750D		
6		0.250D	0.050D	0.900D	0.075D	0.850D	0.100D	0.800D
10	Same as above, plus by 1/2 in. from 3 to 6 in.	0.156D	0.045D	0.910D	0.070D	0.860D	0.095D	0.810D
16	by 1/2 in. from 2 to 6 in.	0.098D	0.045D	0.910D	0.070D	0.860D	0.095D	0.810D

D = major diameter

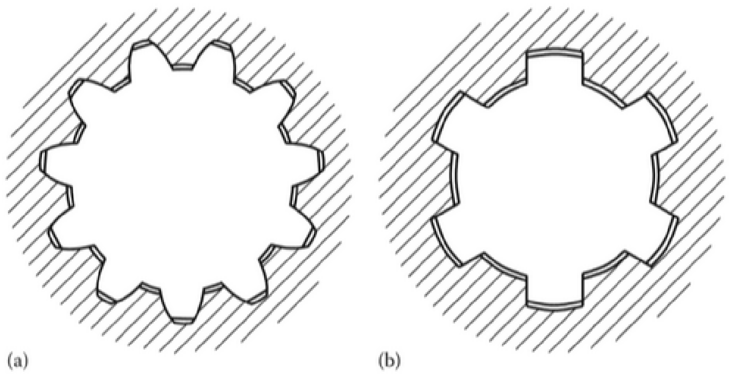
Advantages of Spline Shafts:

1. No relative motion between spline teeth and the shaft ensures a secure connection.
2. Torsion and bending loads are evenly distributed across multiple spline teeth.
3. Lower torsion load per tooth compared to keyed shafts, enabling high torque transmission.
4. Ability to accommodate axial movements while transmitting torque.
5. Efficient manufacturing process with high precision compared to keyed shafts.

Types of Splines:

a. **Involute Splines**:
   - Feature a self-centering design for equal load distribution among teeth.
   - Common pressure angles are 30°, 37.5°, or 45°.
   - Ideal for better connectivity and torque transmission.

b. **Straight-Sided Splines**:
   - Feature rectangular ridges for uniform distribution.
   - Standardized for 4, 6, 10, or 16 splines.
   - Easier to manufacture but less efficient than involute splines.



(a) (b)

Tapered Shafts: Tapered shafts are designed to address stress concentration issues typical of keys and splines. A tapered design ensures a close fit with the mating component, distributing contact pressure uniformly. While effective for high-torque applications, they require precise machining and are costlier to manufacture compared to conventional shafts.

Comparison Between Splines and Keys

	Splines	**Keys**
Torque capacity	High	Moderate
Axial movement	Yes (if designed)	None
Manufacturing cost	High	Low
Load distribution	Excellent (multi-tooth)	Localized (1-2 faces)
Shaft weakening	Minimal	High (stress at keyseat)
Simplicity	Complex	Simple