# Inside Splines

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**Any device that transfers rotary motion from one point to another probably relies on a spline, so it's a good bet that we use them on a near-daily basis. Read on to learn more...**


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What is a spline? According to the *American Heritage Dictionary of the English Language* (fourth edition, 2000), a spline is defined as: Noun: 1a. Any of a series of projections on a shaft that fit into slots on a corresponding shaft, enabling both to rotate together. b. The groove or slot for such a projection. 2. A flexible piece of wood, hard rubber, or metal used in drawing curves. 3. A wooden or metal strip; a slat.

The origin of the word may be derived from the word "splinter," but in today's world a spline had better not splinter or the consequences could be grave.

For purposes of this article, splines are used in mechanical drive systems. They are found in the rotating mechanisms that we all see daily. Any device that transfers rotary motion from an input to an output most likely uses a spline of some sort. Splines transfer the rotary motion of an input to an output through a mechanical connection, or splined shaft. A splined shaft is one that (usually) has equally spaced teeth around the circumference, which are most often parallel to the shaft's axis of rotation. These teeth can be straight sided, included angle forms (serrations) or involute form. The externally splined shaft mates with an internal spline that has slots, or spaces, formed in the reverse of the shaft's teeth. The rotation of the splined shaft is transferred to the internally splined member, such as a gear or other rotary device. The transfer of this rotation is at a ratio of 1:1.

The benefits of using a splined shaft in the place of a keyed shaft are many. The spline connection provides an equally distributed load along the sides of the teeth. This shared load provides a longer fatigue life verses a keyway drive. Different types of spline tooth forms allow for stronger drives, the ability to slide, transfer of rotational concentricity, allowance for misalignment and, in the case of helical spline drives, the transfer of axial and rotary motion at the same time.

## Spline Types

**Parallel Key Spline:** This type has equally spaced teeth that are straight sided. The teeth on the shaft have an equal tooth thickness at any point measured radially out from the axis of rotation. Conversely, the internal parallel spline has corresponding straight sided spaces. This type of spline is similar to a keyway drive, with the exception that the keys are integral to the shaft and equally spaced around the circumference. The piloting feature can be the outside diameter of the shaft and major diameter of the internal spline or the minor diameter of the internal spline and the minor diameter of the shaft. Types of fit are permanent, to slide when not under load, to slide when under load. Types of fits and tolerances are described in the SAE handbook.

**Involute Spline:** Again, this type has equally spaced teeth, but they are not straight sided. The teeth have an involute form, just like a gear tooth. The teeth do not have the same proportions as a gear tooth; they are shorter in height to provide greater strength. This truncated height combined with the involute form sides provide greater strength. There are no sharp inside corners at the base of the teeth as found in parallel key spline drives. Instead, there is a smooth transition through a radius. This decreases the possibility of fatigue cracking in these areas. Involute splines come in several varieties: Flat root side fit, fillet root side fit, and major diameter fit.

The flat root side fit has a slightly larger minor diameter (male) and smaller major diameter (female) than the fillet root spline. The transition area between the side of the tooth (male) or space (female), and the corresponding minor diameter (male) or major diameter (female) exhibits a smaller radius than in the fillet root spline. These splines may be used when strength is needed and fatigue is not of great concern.

The fillet root side fit spline exhibits a full radius in the trochoid area between the teeth on both members. This full radius is tangent to the involute sides of adjacent teeth, providing maximum strength.

The major diameter fit spline has a tightly controlled outside diameter (male) and major diameter (female). The close fit at the major diameters provide for transference of concentricity from the shaft to the female spline. The tips of the male spline teeth are typically chamfered to allow clearance with the radii in the transition area between the sides of the teeth and the major diameter in the space of the female spline. These spline types are specified in metric and English through ANSI and DIN design manuals, and these specifications also provide for classes of fit.

**Crowned Splines:** These splines are typically involute. They can be flat root, fillet root, or major diameter fit. The purpose of this type of spline is to allow for angular misalignment between the shaft and mating detail. This is accomplished by "crowning" the male tooth. The tooth (usually) has a symmetrical crown about the centerline of the spline face-width. At this centerline the tooth thickness is at its maximum. Moving toward the ends the tooth thickness gradually decreases, with the thinnest sections occurring at each end face. The tooth thickness is measured at the pitch diameter. Usually the outside diameter of the spline is also crowned, with the largest diameter occurring at the same location as the thickest tooth thickness, and decreasing proportionally to the designed misalignment toward each end face. The female spline is usually not crowned.

The effect of this is to allow the male spline to "tilt" slightly to the maximum designed angular misalignment. This "tilt" occurs about the centerline established by the intersection of the shaft axis of rotation and the centerline of the spline face-width. The thinner shaft tooth thickness at each end of the face width--combined with the radius, or crowned outside diameter--allows opposite ends of the spline to penetrate deeper into the female spline space as it tilts. This deeper penetration into the spaces effectively allows the shaft to "roll" about the previously described axis intersection, providing for the angular misalignment. Splines of this type are usually designed in conjunction with ANSI or DIN tolerances.

**Serrations:** This type of spline has a tooth form that is non-involute. The teeth of the male detail are in the form of an included angle, with the female serration having spaces of the same included angle. Serrations are generally used on smaller diameter drives, where an involute form would not add strength. Because the teeth are a simple included angle form, more teeth can be used on a small circumference, providing a greater contact area. Serrations are used in instrument drives, valve shafts, and the like. Standards are found in SAE, JIS, and DIN

**Helical Splines:** These can be either parallel or involute tooth form. The helical spline has a specific lead and helix angle. These splines are used for several applications.

In drives where the spline shaft may become torsionally "wound up" (in applications of high torque), a straight spline might lead to drive shaft breakage in areas other than the spline. This is because the load along the straight spline is equal and the stresses are concentrated in areas other than the spline. Introducing a slight helix to the male spline allows an equal "wind" along the entire length of the spline, resulting in full contact along the drive side of the tooth. This load sharing distributes the rotational torque along a greater length of the shaft, which now includes the spline.

In some applications it is desired to combine rotation with axial motion. The use of a helical male and mating helical female spline accomplishes this. When sudden rotation of the axially fixed member is introduced, the helical teeth of the splines slide against each other. This thrusts the axially floating detail forward, or backward, depending upon rotational direction. This type of spline can be used for engagement or disengagement of face couplings through the use of rotary motion.

## Methods of Machining Splines

**Milling:** Serrations and parallel or involute splines can be milled. A double angle milling cutter designed to produce the space of a serration or parallel key splined shaft is used to machine the spaces between the teeth. For involute splines, a milling cutter that has the reverse form of the involute for that specific diametral pitch, pressure angle, and number of teeth would be used to machine these spaces. The use of an index, dividing head, or CNC rotary table provides the index between teeth.

**Hobbing:** All types of external splines can be produced with the hobbing method. A cylindrical hob with the mating rack form of the spline to be produced is the cutting tool. The number of starts of the hob and the number of teeth in the spline determine the ratio that the hobbing machine is geared to produce. The hob then "rolls" with the spline, as a gear would roll with a rack, while the hob traverses the work along the work axis of rotation. The cutting teeth of the hob remove material from the spaces between the spline teeth.

**Shaping:** This method can be used to produce both internal and external splines. A shaper cutter--a disc with a given number of teeth, diametral pitch, and pressure angle--has a cutting edge at one face. The ratio of the number of teeth in the cutter and the number of teeth in the work determine the differential gear train for the shaping machine to provide the specific rotational ratio between the cutter and work. The cutter is then reciprocated along a parallel axis to the work while both cutter and work are rotating. The cutter and work roll together (as a gear and pinion would) while the cutter removes material from the work during the down stroking action. The resulting teeth on the work have generated involute sides.

**Broaching:** This method is used to produce female splines of all types. The broach tool is specific to the internal spline it is designed for. The tool has the correct number of teeth and form for the female spline it is to produce. It has multiple cutting edges, arranged along the length of a cutting tool. The starting end of the broach is a smooth diameter that fits in the smooth bore of the work. Progressing from this end to the opposite end of the tool, cutting edges at predetermined equal axial distances are found. Each cutting edge has a progressively increasing form of the final spline. This allows a specific chip load on each cutting edge as it is pulled or pushed through the blank. Upon exiting, the last rows of cutting edges produce the final spline size.

**Slotting:** This method can be used to produce internal splines, typically parallel key splines. A tool designed to mirror the space of the spline is used in a slotting or shaping machine. The tool is reciprocated along a parallel axis to the work and is in-fed between each stroke. The cutting action occurs on the downward stroke. Upon reaching full depth the tool is retracted to the original starting position, the work is indexed, and the process begins again until all spaces are machined. This method can also be used for external splines, but other methods are usually more efficient.

## Involute Spline Inspection

**Gage pin measurements:** One, two, or three-gage pins of a specific diameter placed in the spaces of the spline can be used to obtain a measurement over or between pins. A gage pin of a specific size will contact the involute sides of the spline teeth. The calculated dimension for the over or under pin measurement, depending upon whether it is an external or internal spline, determines the actual tooth thickness or space width. This actual measurement of the tooth or space width does not take into account any other elements of a spline. Because of this the actual thickness or space width tolerance band begins at the minimum material condition to ensure fit between details.

This method is used in the absence of full composite go and full composite or sector no-go spline gages. Tolerance ranges for differing fit types can be found in the respective ANSI or DIN standards to which the spline conforms.

**Spline gages:** Ring or plug gages, depending upon whether you are inspecting internal or external splines, come in several types:

*Composite:* Composite go and no-go gage sets check the spline to the effective tooth or space width. The effective fit is one that is "tighter" than the actual fit measured by the pin method. The effective fit is intolerant of spacing, involute, or lead error. Both go and no-go gages are made with a full compliment of teeth. The gages are "perfect" in all elements: spacing, lead, and involute. Splines machined to these standards are machined to the effective tooth and space widths. This tolerance band is taken from the maximum material condition and will slightly overlap the actual tooth thickness dimension. It is possible to produce a spline that "takes" the go gage but is still out of tolerance to the actual tooth or space width as measured over or between pins. This is an acceptable condition as the go gage ensures a fit with the mating part.

Were this same part machined to the maximum (internal) or minimum (external) pin measurement calculated from the actual tooth or space width, the composite no-go gage would be accepted by the part. If the requirement were that the acceptance be made by composite gages, this part would not be acceptable.

*Sector No-Go:* Use of this gage allows the whole range of tooth thickness tolerance, from minimum or maximum effective to minimum or maximum actual tooth or space width. In this case a full composite go gage and a sector no-go gage would be used.

The sector no-go gage has two groups of two or more diametrally opposite teeth. These teeth (or spaces on a ring gage) are produced to the maximum actual space width (plug) or minimum actual tooth thickness (ring) part allowance. In effect, if this gage goes the part would measure out of tolerance using the pin measurement. Oversize for an internal, and undersize for an external. Gage-design parameters can be found in the respective ANSI or DIN standards to which the spline conforms. For more information on actual verses effective spline fits, see the article "Actual vs. Effective Involute Tooth Size" by Brian Sloan in the March 2004 issue of Gear Solutions magazine.

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