Back To Basics

Involute Splines

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Gears and Splines

Engineering design requires many different types of gears and splines. Although these components are rather expensive, subject to direct wear, and difficult to replace, transmissions with gears and splines are required for two very simple reasons:

1) Motors have an unfavorable (disadvantageous) relation of torque to number of revolutions.

2) Power is usually required to be transmitted along a shaft.

Due to the increasing number of motor driven components, the use of splines does not diminish, but increases. In general, there are two different kinds of tooth based systems — gears and splines.

Operation of gears

Gears always transmit torque from one axis to another. This is obtained by direct contact or indirect contact through chains or Vee-belts. Usually the number of revolutions is changed at the same time. Examples are spur gears, bevel gears, helical gears, and herringbone gears. (See Fig. 1.)

Throughout the world, gears are the subject of standards, literature, lectures, design classes, seminars, software, and specialists. However, there is very little information on splines. Therefore, from this point, we will deal only with splines.

Operation of splines

Unlike gears, splines are only applied for the transmission of torque on the same axis. Again, in general, splines are necessary for only two reasons.

1) Parts with torque transmission have to be separated due to production and assembly requirements. (Transmissions, steering components)

2) The driven part must be movable on the driving part. (Speed reducers, clutches)

The main criterion for splines is secure torque transmission. Additional requirements are little clearance, good centering, low noise, low wear, and few axial forces. These demands are very high for a part of such geometric complexity.

The requirements and designs vary depending on the kind of use. Accordingly, there are many names for these spline forms:

- Fit splines
- Straight-sided splines
- Splined shafts and hubs
- Sliding profiles
- Short splines
- Serration shafts and hubs

The designation "spline" serves as a title for all profiles of the above types which are inserted into one another, (See Fig. 2.) with the exception of the racktooth system. This system functions similarly in some respects, however, it has to be regarded separately from splines. Although it transmits torque axially, it cannot be simply inserted into the mating component, but rather requires an additional axial pressure force. (See Fig. 3.)

Splines and Forms of Flanks

The flank form of splines is not of consequence in actual operation. In practice there are only three different forms of tooth flanks between minor and major diameters.

Straight-sided

Straight-sided profiles have keys (teeth) with straight and parallel tooth flanks. (See Fig. 4.) The number of teeth varies from 4 to 12. The large tooth thickness from minor to major diameter allows the transmission of very high torques. However, there is a lack of centering efficiency in the straight-sided tooth flanks, therefore, the centering has to be on the minor and major diameters. The torsional clearance must then be increased to take eccentricity of the tooth flanks to the centering diameter, as well as the spacing errors which always exist, into account. With wear, there will quickly be an additional radial clearance and, at the beginning, little line of contact. (See Fig. 5.) There is a further disadvantage for all straight-sided splines regarding the line of contact. A surface contact will only exist on the flanks after wear or when bending forces occur.

Serration

Serration splines have straight flanks similar to straight-sided splines, however, they are angular. This angle causes a centering effect of the tooth flanks and does not require any additional diameter centering fit. (See Fig. 6.)

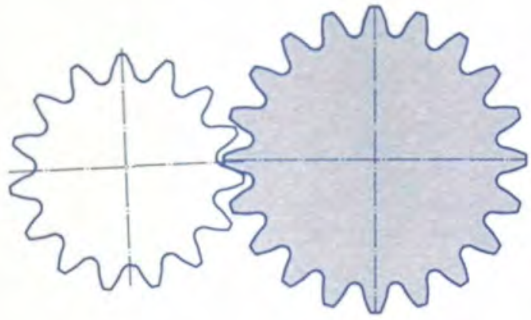


Fig. 1 – Mating spur gears.

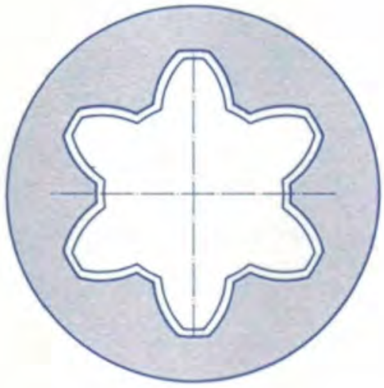


Fig. 2 – Matching splines.

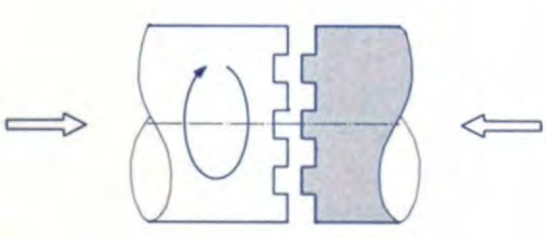


Fig. 3 – Mating rack-tooth system.

Fig. 4 – Straight-sided profile.

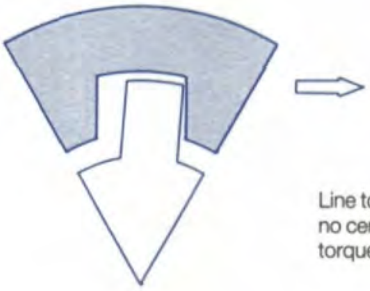


Fig. 5 – Straight-sided profile 1 tooth.

Fig. 6 – Serration.

AUTHOR:

RUDOLPH OCH *is president and owner of Frenco, a West German manufacturer of spline and profile-related gaging and workholding equipment. He is a graduate mechanical engineer and holds several patents for spline gages, arbors, and testing methods. Mr. Och serves on the ANSI spline committee.*

Favorable flank angles are between 50° and 90°. However, the teeth are rather small compared to straight-sided splines and, therefore, the transmission torques are very low. (See Fig. 7.) A second disadvantage is that line contact cannot be eliminated by serration due to the straight flanks. Therefore, serration splines are sensitive to wear and are only used for non-moveable connections.

Involute

Side fit. At present the best connection is achieved by the use of involute tooth flanks. (See Fig 8.)

The contact of tooth and space is always a surface independent of the fit clearance. This characteristic can only be obtained with the involute form.

The centering effect is very good, and the distribution of force from top of the tooth (addendum) to root of the tooth (dedendum) results from the involute curve. (See Fig. 9.) Splines with involute flanks have a very high line of contact in the nonworn condition. This reduces increase of clearance due to wear within the lifetime of the spline, compared to straight-sided splines. For these reasons the spline with involute flanks is the most frequently used connection. (See Fig. 10.)

The tooth flanks can optionally be made steeper or shallower by varying the pressure angle. Different pressure angles influence force transmission, notch effect, and producibility. Pressure angles of 30°, 37.5°, and 45° are most commonly used.

Diameter fits are possible with involute flanks for systems having great numbers of revolutions at high speeds. That necessitates more precise centering and reduced runout. In practice, these fits are rarely used. Side fit splines with involute flanks are in the majority and offer the biggest range of use.

Diameter fit. Both torque transmission and centering are done on the tooth flanks at the same time with side fit profiles. Therefore, the precision of the centering depends on the quality of production of the tooth flanks. Here certain difficulties arise, as the tooth flanks are not ground for reasons of economy. But if a very precise centering is important for operation, it is possible to produce a considerably more accurate centering using minor and major diameters. (See Fig. 11.) These are special cases which result in extra cost, yet, are cheaper to produce than ground tooth flanks. Usually a major diameter fit is chosen in these cases. The major diameter of the internal spline is broached exactly, (using a concentricity broach) and the major diameter of the external spline is ground cylindrically. This provides the most economical production of a diameter fit.

Different pressure angles. Depending on the pressure angle, the tooth flanks become steeper or shallower. The most commonly used pressure angles are 30° for sliding fits and 45° for force (interference) fit. The pressure angle of 37.5° is rarely used. (See Fig. 12.)

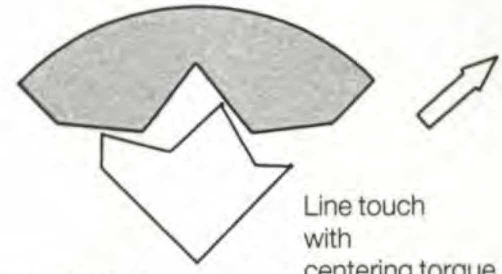


Fig. 7 – Serration profile 1 tooth.

Fig. 8 – Involute spline.

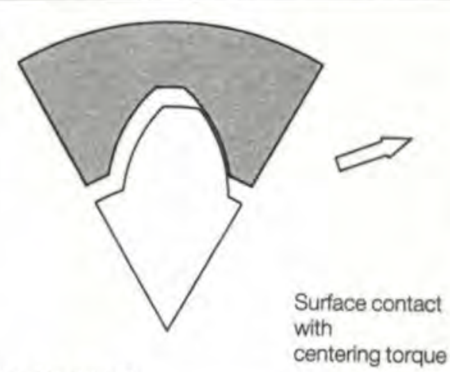


Fig. 9 – Involute spline 1 tooth.

Fig. 10 – Involute spline with load.

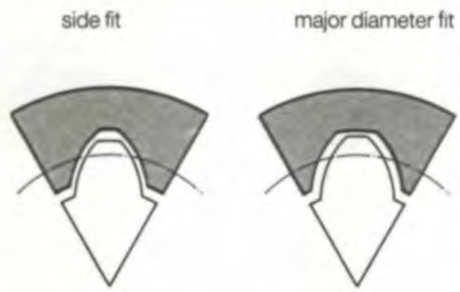


Fig. 11 – Possibilities of fits.

Fig. 12 – Pressure angles.

Pressure angle 30° is the most common profile for sliding fits. Relatively high torques are transmissible. This pressure angle is not very advantageous for the production process "rolling", due to the necessary high volume portions of deformation.

With a 45° pressure angle the centering effect is very good. There is, however, more wear due to the smaller tooth heights with sliding connections. The increased notch effect demands a (full) fillet root. This pressure angle is ideal for the production process "rolling", therefore, it is the angle of preference for force fits.

Pressure angle 37.5° is a compromise between 30° and 45°. Such profiles are often used for the advantage of a 30° spline (rigidity, stability, tightness of fit), but to avoid the disadvantages of the 30° to manufacture. Sometimes, this pressure angle is used for reasons of reducing the notch effect on thin wall mating parts.

Geometry of minor and major diameters. Splines with pressure angles of 30° commonly have flat addenda and root radii. Splines with 37.5° or 45° pressure angles are generally made with fillet roots and flat addenda because of the notch effect. Diameter fits often possess tip chamfers due to root radii arising in production of the matching parts. (See Fig. 13.)

In addition to the minor and major diameters, the form diameter at the root is always required. (See Fig. 14.)

Side Fit Profiles

Clearance of fit

Side fit profiles obtain both the centering and the torque transmission with the tooth flank contacts. Under load, the centering effect is independent of the torsional clearance of the internal spline to the external spline. However, in a no-load condition, a gap occurs between the internal and external profiles, and the resultant centering effect degenerates with direct relation to the amount of gap.

For the above reason, it is desirable to have as small a gap as possible, creating a close fit clearance between tooth and space. (See Fig. 15.) To attain this effect, close manufacturing tolerances must be maintained. In practice, however, standard production processes produce an ever increasing fit clearance over time. In special cases, a negative fit clearance in the form of an interference fit is required. In production, the amount of interference is very difficult to control and is subject to the same fluctuations as a clearance fit.

Contact area

Of all form fitting connections, splines are among the most difficult to calculate and predict. For example, a standard 1.00" spline with 24 teeth has 48 individual lines of contact. When an internal and external spline each having 24 teeth are

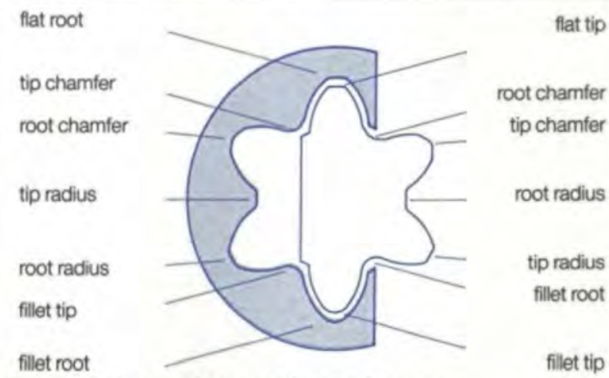


Fig. 13 – Geometry of minor and major diameters.

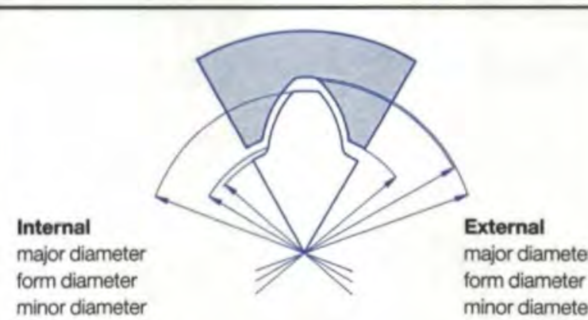


Fig. 14 – Diameters.

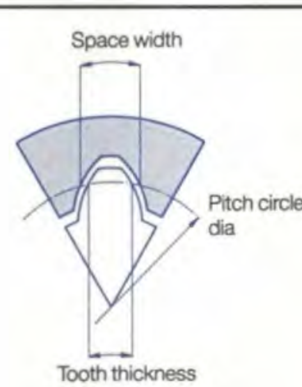


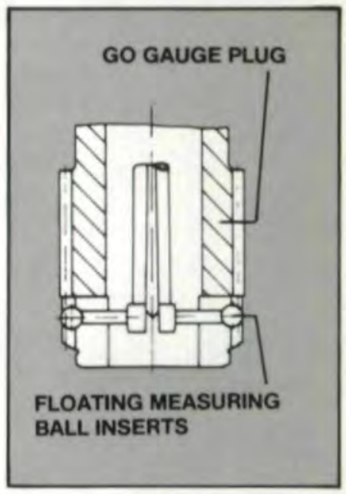
Fig. 15 – Tooth thickness space width.

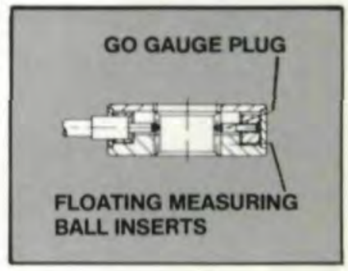
FRENCO GAGES FOR COMPLETE INSPECTION OF INVOLUTE SPLINES

Chart of actual and effective spline conditions

	Tolerance zones	SPC — Histogram
INTERNAL SPLINE	max. size between balls — REF. min. size between balls - - - go gage plug —	
EXTERNAL SPLINE	go gage ring — REF. max size over balls - - - min. size over balls —	

ILLUSTRATIONS





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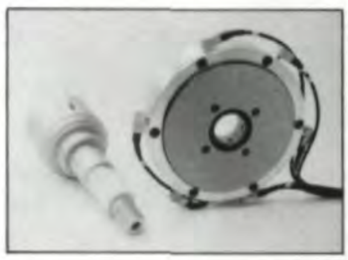
EXAMPLES:

Indicating spline plug gage type 1x1



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inserted together, the design theory is to have any equal symmetrical fit clearance at all 24 teeth. However, inspection of the mating profile systems shows some spaces to be slightly smaller or slightly larger than others. The smallest widths of the internal spline are entirely responsible for the efficiency of the entire spline system.

The equal distribution of size and form fluctuations within both profiles directly influences the number of contacting tooth flanks under load. For clearance fit designs, this number is not important. However, on interference (force) fits, the line of contact at the tooth flanks has an enormous effect on the necessary force required during assembly. A poor line of contact influences performance of the spline as well as increases fatigue of material. As a rule it is desirable to have a good line of contact, and this can only be obtained by designing and manufacturing splines with little size and form deviations within the profile.

Effective spline

In rare cases, when an internal spline is mated with an external spline, the quality of fit may resemble a cylindrical (non-profiled) fit. In side fit profiles, this fit is achieved through perfect contact of the tooth flanks with the spaces. The same applies to the system basic sleeve — a basic shaft where an absolutely round and cylindrical bore or shaft will never be possible. Likewise, a spline will not be absolutely round or equally cylindrical over its entire length. Production is responsible for nonuniformities of form where irregularities will always exist.

Not only the size, but also the existing form errors are important for the clearance of the fit. The amount of influence of size and form to the clearance fit is different on various contours.

With regards to cylindrical (non-profiled) fits, the actual size of the components determines the fit much more than the form. Also a cylindrical form can be produced more easily and accurately.

The converse is true with splines. Splines only can be produced with relatively big deviations. The quality of fit of a round bore is always determined by the internal effective circle, and the fit quality of a shaft by the external effective circle.

Form errors reduce the effective size of bores and increase the effective size of shafts. (See Figs. 16-17.) Cylindrical fits always have form deviations, however, they are not as big as for splines. If accurate round fits are requested, they will be ground after heat treatment. The grinding of a round geometry is an acceptable and economic solution.

The cost of grinding splines is prohibitively high and is a process that is usually avoided. Even with the need for hardened structural parts, a rework usually will not follow heat treatment. At the time of production of soft (green) splined parts, big form deviations arise. Additionally, heat treatment makes the deviations of contour worse. The effective tooth thickness and space width are greatly influenced by

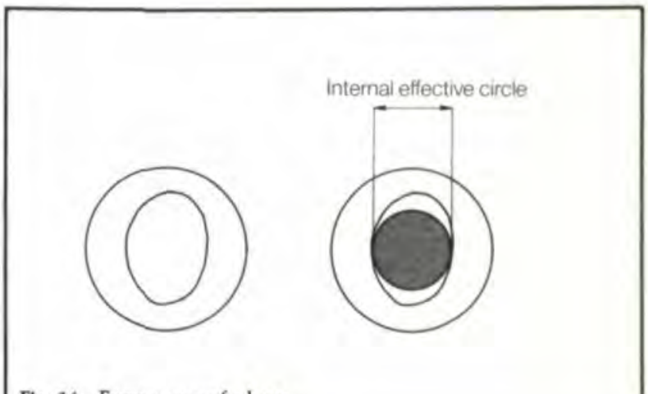


Fig. 16 – Form errors of a bore.

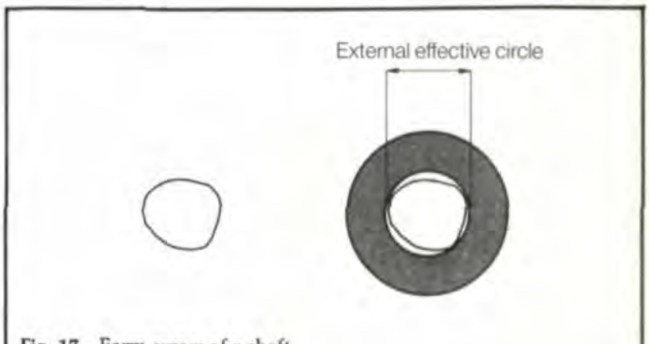


Fig. 17 – Form errors of a shaft.

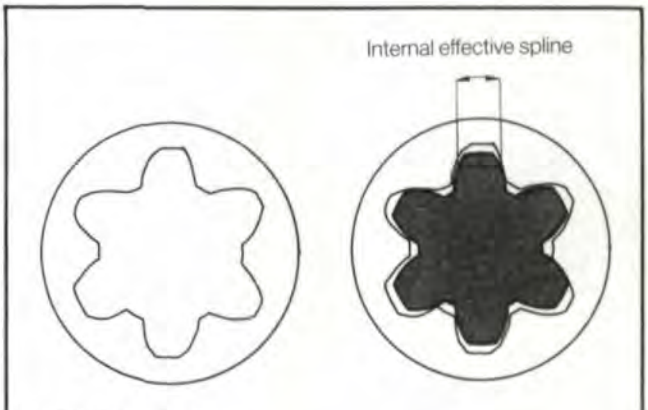


Fig. 18 – Internal spline.

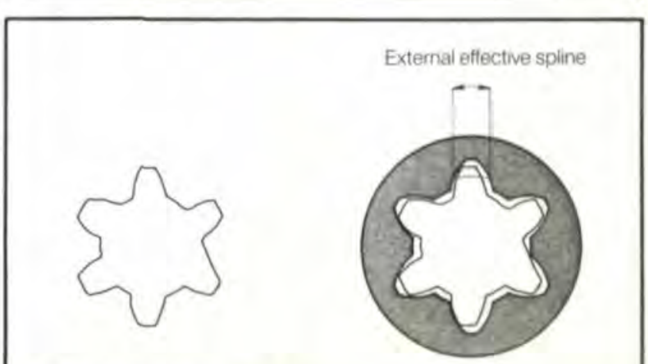


Fig. 19 – External spline.

these factors. The effective tooth thickness and space width are termed the "effective spline". (See Fig. 18-19.)

Fit system actual-effective

The actual (real) measurable size of tooth thickness and space width at the pitch circle diameter (PCD) is called "actual". The more difficult to measure size of the tooth thickness and space width which makes the effective spline, is called "effective".

The compounding effect of many form errors cause an increased effective tooth thickness on external splines. This makes the external spline appear to have a larger actual size than the mating part. The compounding form errors on internal splines result in a reduced effective space width. As above, this makes the internal appear to have reduced actual size as compared to its mating part.

The most important form errors occuring are

a) Profile error. (See Fig. 20.)
b) Spacing error. (See Fig. 21.)
c) Lead error. (See Fig. 22.)

In addition to these primary deviations, the following errors may also exist:

Concentricity error
Torsion (twist, distortion)
Damage
Eccentricity
Dirt contamination
Surface finish deviation

The summation of all the single form deviations can only be determined by fitting of an "ideal" mating part (go gage).

Unlike cylindrical fits, the manufacturing tolerance and the form tolerance are distinguished separately on splines. The manufacturing tolerance is the tolerance of the space width and tooth thickness at the circular pitch diameter. This is a required measurement for the adjustment and wear of tooling. The common designation for this specification is "actual" tolerance, and from this the size "max actual" and "min actual" are derived. (See Fig. 23.)

In addition to the actual manufacturing tolerance discussed above, splines will also have form deviations. These form errors ultimately decrease the apparent size of the spaces on internal splines and increase the apparent size of the tooth thickness on external splines. This size is called "effective". (See Fig. 24.)

Much like the deviation of size having a tolerance due to unavoidable process changes in production, deviations in form also have tolerance band governing the total amount of errors. The name of this "form deviation" tolerance band is "effective tolerance".

Internal splines have a decreasing tolerance limit called "minimum effective", which is the minimum size of the internal effective spline. External splines have an increasing effective tolerance. The limit of the external effective spline is called

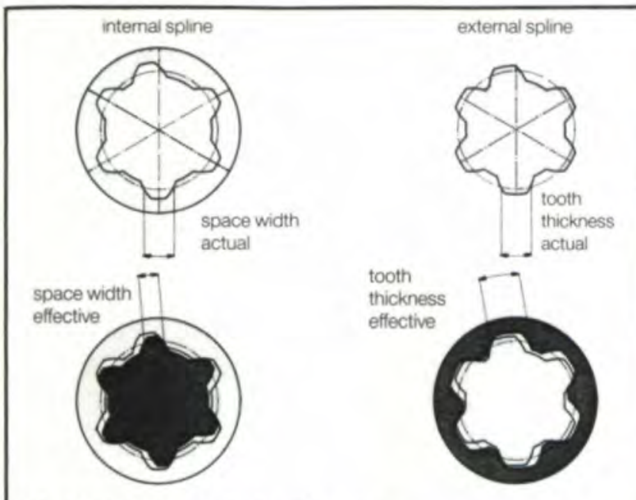


Fig. 20 – Effective result of profile errors.

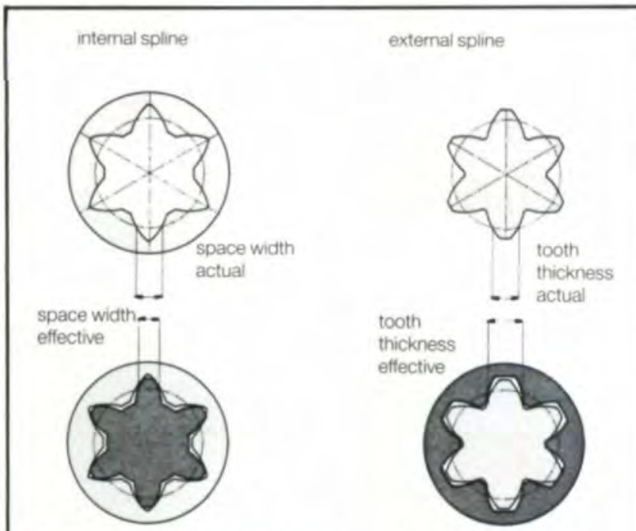


Fig. 21 – Effective result of spacing errors.

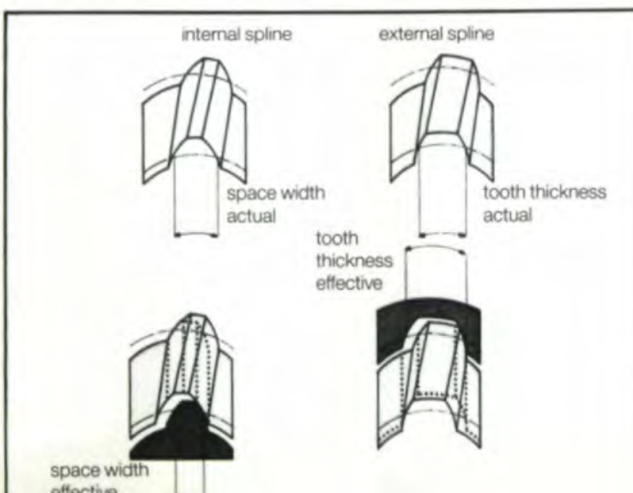


Fig. 22 – Effective results of lead errors.

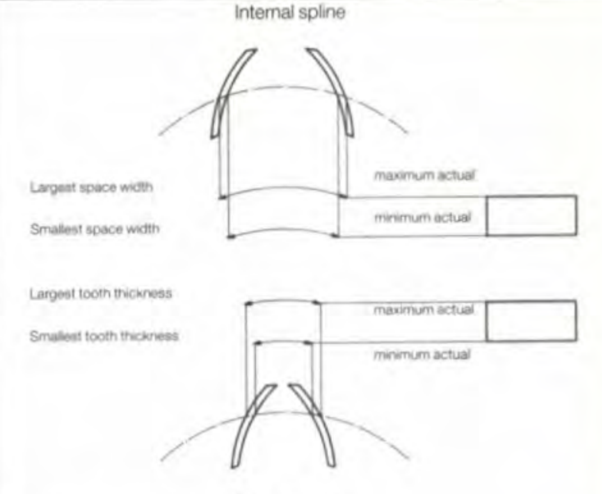


Fig. 23 – Size tolerances.

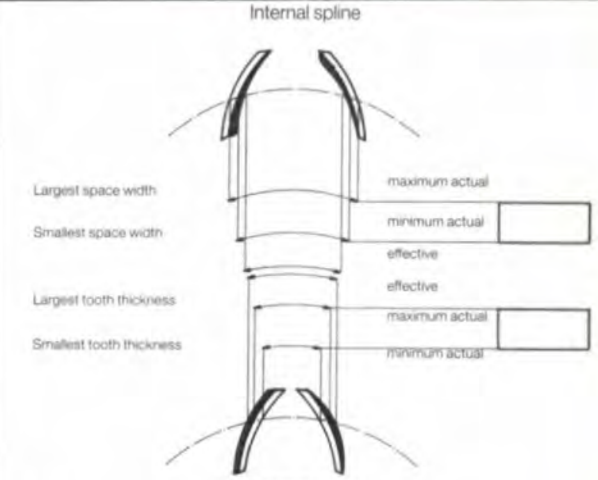


Fig. 24 – Size tolerances and effective errors.

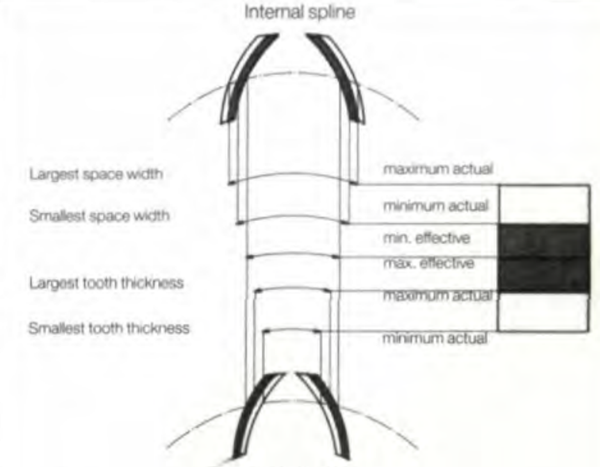


Fig. 25 – Tolerance system.

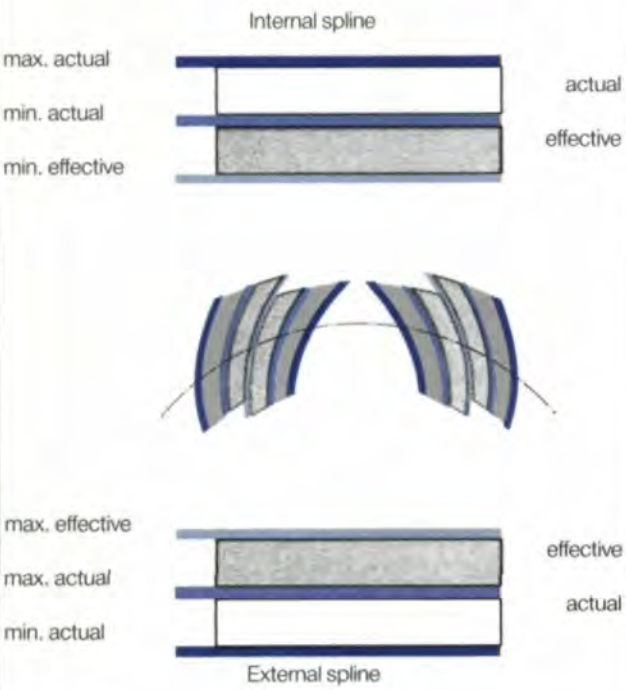
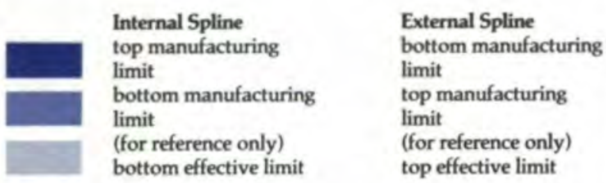


Fig. 26 – Tolerance limits.



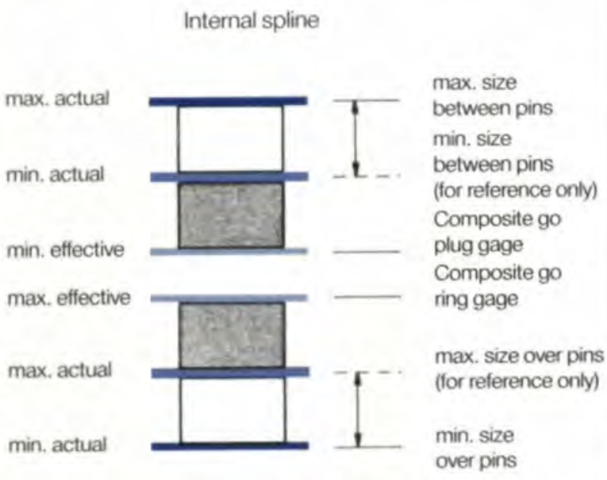


Fig. 27 – Spline tolerancing system using no-go gages.

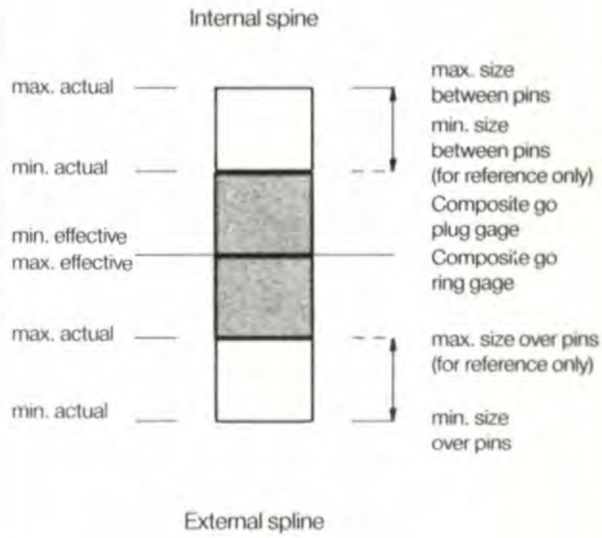


Fig. 28 – Two-tolerance zone system.

"maximum effective". (See Fig. 25.)

Fit diagrams

To show the tolerance zones (ranges) the block diagram seems to be most suitable. (See Fig 26.) The tolerance limits are as follows:

Internal spline: The red tolerance limit (maximum actual) is converted to the measurable feature "dimension *between* pins". The minimum actual limit only serves as reference for manufacture. The minimum effective clearance of the spline is checked as an attribute with a go gage plug.

External spline: To measure the red tolerance limit (minimum actual) convert it to dimension *over* pins. In this case, the limit "maximum actual" only serves as a manufacturing reference. The maximum effective spline is checked by a go ring gage.

Spline standards allow the use of sector no-go gages in place of measurement between/over pins. This method of size measurement, however, may not be 100% accurate. Size measurement must see as few form errors as possible. No-go sector gages will check profile errors as well.

The simple fit diagram is very helpful in understanding this spline tolerancing system. (See Fig. 27.)

The use of the two-tolerance zone system has never been more important than now. (See Fig. 28.) The increasing emphasis on quality and maximum material condition measurement helps us understand the need for continued use of this tolerance system in the future. □