Design Parameters for Spline Connections

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Introduction

Splines are machine elements that connect a shaft with a rotor. Next to transmitting torque, the spline might also be utilized to center the rotor to the shaft. It is interesting that the spline's tooth profiles are involutes, although the involute profile does not contribute to the torque transmission, nor is it linked to the centering function. The reason for the involute profile is the fact that most external splines are manufactured by hobbing with a standard straight-sided, symmetric hob tooth profile that is fast and delivers good accuracy results. The internal spline has to be manufactured with shaping or broaching, using an involute cutting tooth profile. The nomenclature and parameters of a typical spline connection are presented (Fig. 1). The spline connection in Figure 1 is neither centering on the flanks nor on its major or minor diameters.

The exception to the involute profiles is the parallel straight profile spline that requires a planning operation for the external member and a single tooth shaping or broaching of the internal member. Splines can be organized into 2 main categories and 4 sub-categories that are defined by national and international standards; an overview is given (Fig. 2).

Studying the literature teaches that many large OEM's pick the design proposals, the tolerances and function features for one particular spline design from several standards. Here it will be proposed to use metric units for all calculations, applying the addendum/dedendum recommendation by DIN and following the ANSI guideline for side fit and major diameter fit. In order to eliminate the confusion that the design by picking dimensions and tolerances from different standards might cause, the following sections present a firm guideline for each step of the design, tolerancing and cutting tool definition.

The Different Spline Functions and the Required Fits

If a splined shaft that is, for example, the output of a transmission drive with a rotor that is mounted on its own bearings, then the function of the spline is not the centering of the rotor but merely torque transmission. In this case, a centering function would just cause the transfer of misalignment and runout between shaft and rotor, which leads to vibration and bearing wear. The described connection should have backlash between the flanks and clearance between the top of the internal and external teeth and their adjacent roots, and use a profile fit with backlash (Fig. 3).

If a splined shaft is connected with the internal spline, for example — at the output of a transmission — and if the shaft is long in relation to its diameter, then a flank-centered fit as shown (Fig. 4) is preferred. In order for correct flank centering, the backlash between the internal spline teeth and the shaft spline teeth must be zero. To achieve such a transitional fit, the tolerances according to ISO 7H (shaft spline) and 7n (internal spline) are recommended.

In a case where a rotor like a sprocket is radially centered by the spline connection, then major diameter transition fit (or interference fit) according to ISO (outside shaft diameter tolerance H7 and major internal diameter tolerance n7 (or H7/p7 for a press fit) can be used (Fig. 5). The profiles can be made with backlash or as transition or interference fit (see tolerance recommendations in connection with Figs. 3 and 4). The decision regarding the flank fit depends on the operation schedule

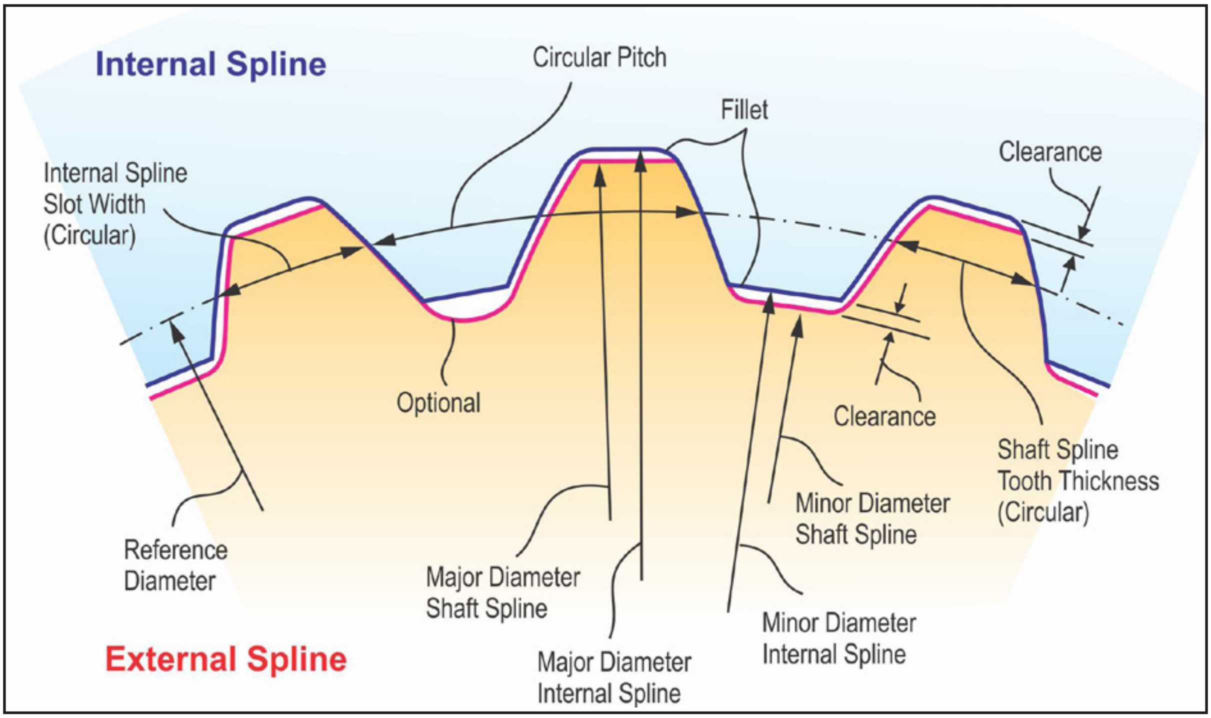

Figure 1 Design parameters for splines.

Involute Splines with Pressure Angle Splines with Parallel Straight Profiles			Parallel Straight Profiles with Corner Checks
ANSI B92.1	DIN 5480 & ISO 4156	JIS B1603-1995, D2001	AGMA 945-A18 & ISO 14
α = 30º, 37.5º, 45º	α = 30º, 37.5º, 45º	α = 20º, 30º, 37.5º, 45º	Pressure Angle Formula see Standard
Addendum Formula see Standard	Addendum = 0.45·m Dedendum = 0.55·m Broaching Dedendum = 0.60·m Hobbing	Addendum and Dedendum Definition lean towars DIN & ISO	Use ANSI or ISO Standard for Addendum and Dedendum
Min space width equal max tooth thickness, in case of Interference fit in-crease internal spline tooth thickness	ISO "H" tolerance for external shaft diameter. For internal major diameter use "a to h" for clearance fit, use "h to p" for a gentle fit and "p to z" for press fit	Regarding fit lean towards DIN & ISO	Regarding fit use ANSI or ISO Standard
Root fillet radii with either profile side fit or backlash and always clearance at the major and minor diameter			
Flat root with sharp fillet corners with major diameter fit, backlash and clearance at minor diameter (DIN-ISO also covers a minor diamater Fit)			
Flat root with sharp fillet corners with either profile side fit or backlash and always clearance at major and minor diameter			

Figure 2 **Overview of different spline categories [1 through 7].**

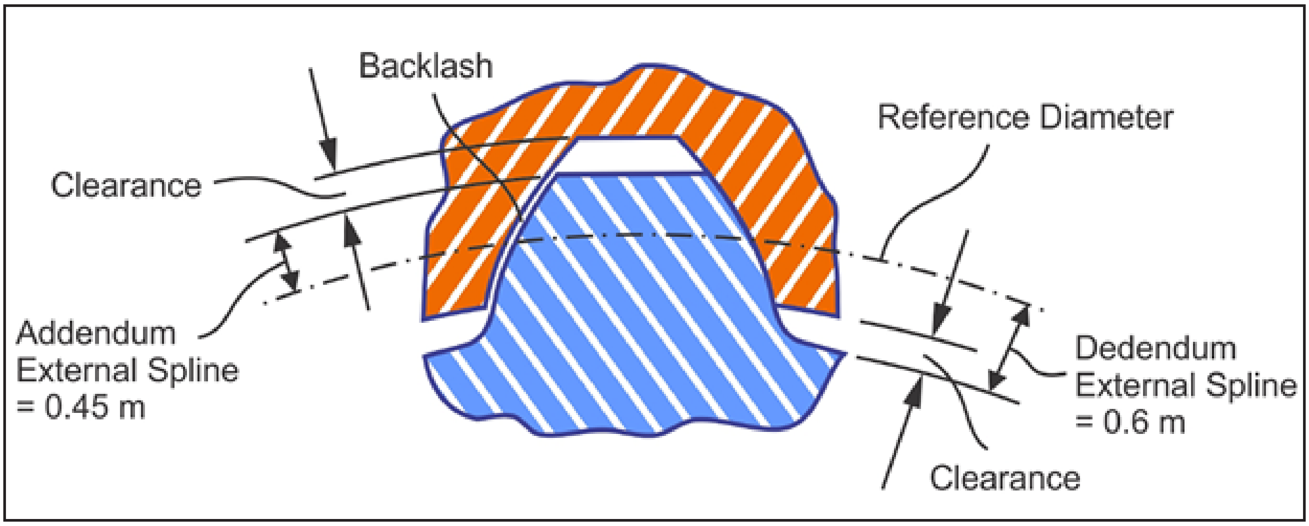

Figure 3 **Not centering connection.**

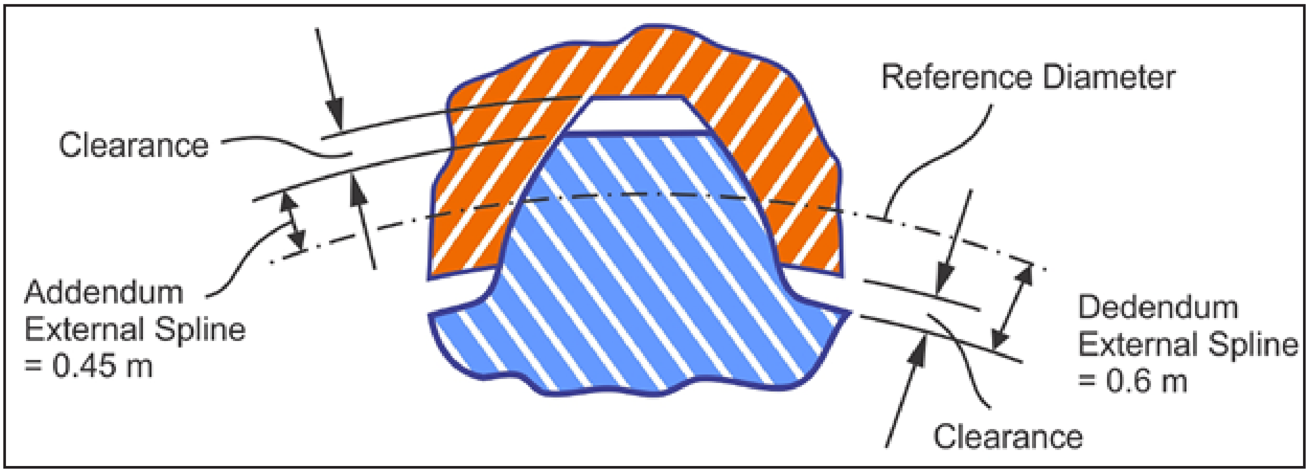

Figure 4 **Flank centered connection.**

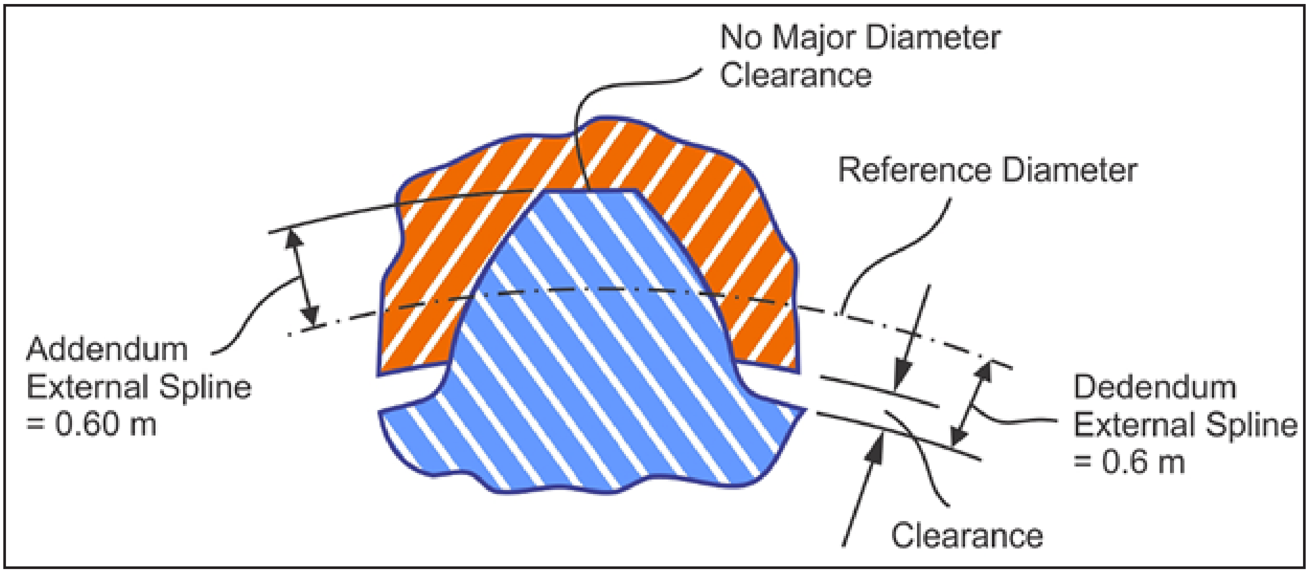

Figure 5 **Major diameter centered connection with gentle flank fit.**

(one-directional or two-directional torque transmission).

The parallel straight-sided spline has straight-sided teeth on the spline shaft and straight-sided slots on the internal spine. To calculate addendum and dedendum, the formulas either from the ANSI or the ISO standard can be used. In a metric calculation like that shown before, the ISO tolerance recommendations are appropriate for diameters and tooth thickness versus slot width. An example for a straight-sided spline is shown (Fig. 6).

The effective pressure angle can be calculated from the triangle in Figure 6, using the reference diameter as hypotenuse and the tooth thickness as the opposite side. The straight-sided spline according to AGMA has checks at the root fillets (Fig. 6). There is no particular preference in the standards regarding diameter fit or flank fit. Also, for the parallel-sided spline it is common to either use a major diameter fit with clearance on the flanks or a major diameter fit with a gentle fit or press fit on the flanks. Flank fit without major diameter fit is uncommon because a radial misalignment due to a press fit is more likely than is the case of splines with non-parallel flanks.

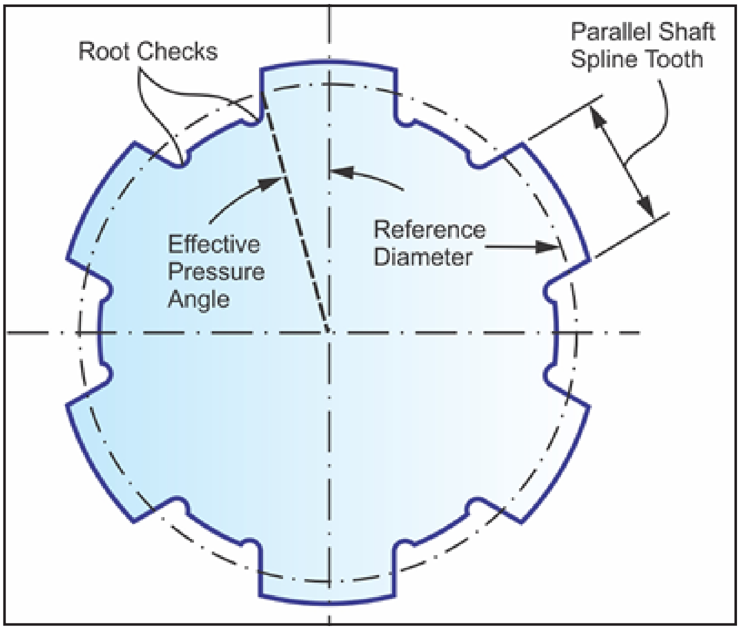

Figure 6 **Parallel straight sided spline.**

Defining Spline Dimensions

The example spline (Fig. 7) transmits the torque of a sprocket to the splined shaft (or vice versa) and centers the sprocket radially. The example sprocket spline has metric dimensions. Although it is proposed in this article to use metric dimensions for all calculations, later, for the search of a suitable standard hob, the module can be converted into diametral pitch in order to find the closest hob — either in the metric or in the imperial system.

The tooth depth is calculated using the difference between major and minor diameter divided by two:

$$\text{Depth} = (d_{Major} - d_{Minor})/2 = 2\,\text{mm}$$

The tooth proportions addendum and dedendum relate the depth to the still-unknown module:

$$\text{Depth} = h_K + h_F = 0.45 * m + 0.60 * m$$

This relationship allows to calculate a module of:

$$m = \text{Depth}/1.05 = 1.905$$

With the known module it is now possible to calculate addendum and dedendum:

$$\text{Reference addendum: } h_K = 0.45 * m = 0.857\,\text{mm}$$
$$\text{Reference dedendum: } h_F = 0.60 * m = 1.143\,\text{mm}$$

Both dimensions, h_K and h_F, are reference values that split the tooth depth into the reference addendum and the reference dedendum. This means that neither of the values is related to the pitch circle. The pitch diameter is calculated like for a standard spur gear by multiplying the module with the number of teeth:

$$d_0 = m * z = 22.857\,\text{mm}$$

It can be recognized that the pitch diameter is smaller than the minor diameter of the spline. Because the spline is not a meshing gear member, there is no working pitch diameter and the meaning of the pitch diameter is primarily important for the choice of the hob cutter and/or the broach. However, it is meaningful to calculate a reference diameter that separates the reference addendum and the reference dedendum:

$$d_{Ref} = d_{Minor} + 2 * h_F = 26.286\,\text{mm}$$

The difference between the pitch diameter and the reference diameter can now be used to calculate the profile shift, which is:

$$x * m = (d_0 - d_{Ref})/2$$
or:
$$x = (d_0 - d_{Ref})/(2 * m) = -0.9$$

The initially calculated module of 1.905 mm will not allow utilizing a standard broach for the internal sprocket spline. If the module is now rounded to a number from the DIN/ISO table of preferred modules, then the rounding to 2.0 mm is proposed.

Rounded module: $m_{Final} = 2.0\,\text{mm}$

This module rounding is without any tangible consequence if the spline shaft, as well as the sprocket spline, are together in the design and manufacturing planning stage. If the sprocket design is done for an aftermarket purpose, and has to fit on an OEM shaft spline, then the working pressure angle at the reference diameter might show some mismatch. In the present case the rounding was only small and pressure angle mismatch will be within an acceptable tolerance.

With the new, rounded module the previously calculated addendum and dedendum values have to be preserved. However, the original factors for the calculation of addendum and dedendum ($h_K = 0.45 * m$ and $h_F = 0.60 * m$) have changed by the module rounding. This fact is not relevant, because the *mm*-value of the sum of addendum and dedendum remain the same, as well as the top-root clearance.

After the module rounding, the pitch diameter and the profile shift factor have to be recalculated:

$$d_{0Final} = m_{Final} * z = 24.00\,\text{mm}$$
$$x_{Final} * m_{Final} = (d_{0Final} - d_{Ref})/2$$
$$x_{Final} = x_{Internal} = (d_{0Final} - d_{Ref})/(2 * m_{Final}) = -0.572$$

The spline set always has a V0 profile shift relation which means:

$$x_{Internal} + x_{External} = 0$$
and
$$x_{External} = -x_{Internal} = +0.572$$

Defining the Spline Pressure Angle

If the splines are being designed, then one of the preferred pressure angles from the standards should be used. ANSI and DIN offer the choice between 30°, 37.5° and 45°. In the JIS standard also a pressure angle of 20° is proposed.

If the spline is designed for an aftermarket product (for example the sprocket shown Fig. 7), then a simple measurement — preferably on a CMM or with a Vernier caliper as shown (Fig. 8) — can be conducted to obtain a first pressure angle estimation. If the aftermarket product is the sprocket (not the shaft), then it would be desirable to obtain the measurement explained in Figure 8 on the spline shaft.

The measurement results are used together with the depth of the spline tooth to calculate the approximated pressure angle:

$$\alpha_{approx} = \arctan[2 * Depth/(t_1 - t_2)]$$

For the example in Figures 6 and 7 with a topland $t_2 = 2.60\,\text{mm}$, a root width $t_1 = 7.30\,\text{mm}$, and a depth of 2.0 mm the

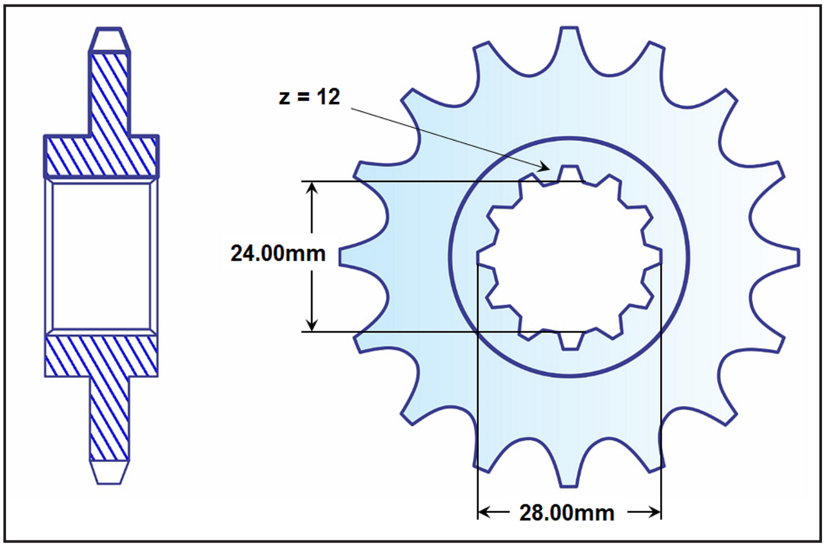

Figure 7 Example sprocket with internal spline.

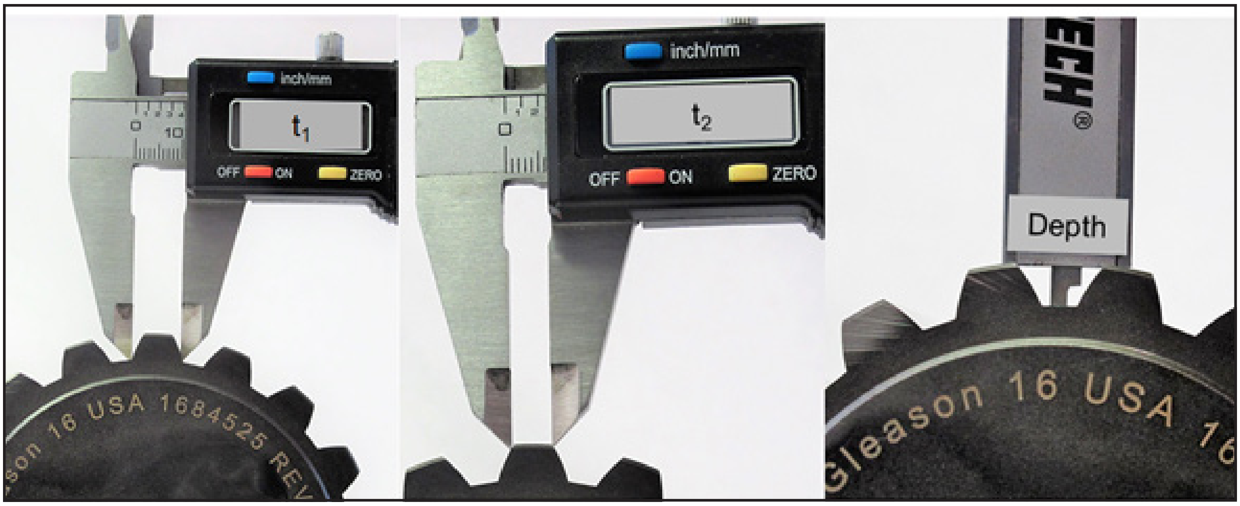

Figure 8 Measurement of topland root and depth.

approximated pressure angle is:

$$\alpha_{approx} = \arctan[2 \cdot 2.00/(7.30-2.60)] = 40.39°$$

The approximated angle is between the preferred angle 37.5° and 45° from the standards. The difference from 45° is 4.61° and the difference from 37.5° is only 2.89°. The decision therefore is 37.5°:

$$\alpha_{External} = \alpha_{Internal} = 37.5°$$

37.5° is a popular pressure angle for splines, which also indicates that the result of measurement and calculation is realistic. It is recommended that the major diameter of the sprocket is equal to the outside diameter of the spline shaft to assure a major diameter fit. If the sprocket is the transmission output of a uni-directional unit, then the flanks can receive a small backlash (e.g. — sprocket spline tooth thickness tolerance ISO 7H and shaft spline tooth thickness tolerance 7f). If sprocket and spline have to transmit torque in frequently changing directions, then a transition fit or a press fit of the spline teeth is recommended (sprocket ISO 7H, shaft ISO 7n).

The tolerance of the major diameter of the internal spline should be selected as a transition fit; for example, ISO H7 (the outside diameter of the spline shaft should be ISO j7).

Defining Tool and Cutting Parameters

The tool for the spline shaft can be a standard ISO spline hob cutter module 2.0 with a pressure angle of 37.5° and sharp corners at the hob teeth. Due to the profile shift of $x_{External} = +0.572$, the hob cutter must be retracted from the theoretical position by $x_{External} \cdot m = 1.144$ mm away from the shaft.

The tool for the internal spline can be a standard ISO spline shaper cutter, for example, with 8 teeth. The center distance between shaper cutter and internal spline is:

$$\text{Center Distance} = d_0/2 - x \cdot m - d_{0Cutter}/2$$
$$= 24.00/2 - (-0.572) \cdot 2.00 - (d_{0Cutter}/2 + m \cdot x_t)$$

A profile shift of the shaper cutter x_t might be required with the low number of cutter teeth, and is therefore considered in the center distance formula.

Summary

This article provides a guideline for the selection of a suitable standard in connection with the kind of spline to be designed and manufactured. Some basic formulae have been explained, together with a strategy on how to find standard tooling by calculating an appropriate profile shift factor for the spline to be designed. If an aftermarket part like a sprocket should be matched to an existing spline shaft, then the dimensions of major and minor diameter can be found on the shaft. Addendum and dedendum have to consider the recommended top root clearance (on the not-centering top root combination). If those facts are all taken into consideration, then it is not important to know if the mating, existing shaft was manufactured with an English standard hob and the sprocket is manufactured with a metric standard hob; this is as long as both members use the appropriate profile shift, which will assure that the reference diameters of shaft and internal spline are identical. Also, a simple method for determining the pressure angle of an existing spline has been presented. The result was compared to the ANSI and ISO table of recommended spline pressure angles which allowed a mature choice of the closest value.

The final section of the article aids in the selection of a hob cutter for the shaft and a shaper cutter for the internal spline. For the correct setup of the manufacturing machine the calculation of the center distances between work and tool was presented.

For more information. Questions or comments regarding this paper? Contact Dr. Hermann Stadtfeld at *hstadtfeld@gleason.com*.

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Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear References Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards — one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau — thus helping to shape and ensure the future of gear technology.