1.0 General

Geometrically, a part can be said to be round (circular), in a given cross section, with a point from which all points of the surface are equidistant. In practice, however, the radius of nominally round parts tends to vary from point to point around the periphery from a center. Surfaces of circular cross section are originally generated by revolving about, or with reference to, fixed point axes. These points, axes, and lines of contact with the part are never perfect. Deflections and imperfect rotation occur as the surface is generated because of imbalance, erratic cutting action, inadequate lubrication, wear, defective or incorrect machine parts, and poor part geometry. These deflections are usually a deviation from circularity (roundness), in the form of lobes, waves, or undulations about the surface of the part. The number of lobes or waves can vary from two to several hundred; two to fifteen lobes are generally generated by the manufacturing process. Out-of-roundness may also result from distortion of the part by chuck jaws, fixtures, localized heating, excessive feeds, and warped or out-of-round stock. So that the correct measuring method can be selected, it is important to know the characteristics of the lobes. For example, the out-of-roundness of a part with an odd number of evenly spaced lobes cannot be detected by measuring the diameter. Out-of-roundness is also distorted in magnitude when V-block methods are used. In addition, certain lobe patterns cannot be detected in a V-block. All of these factors that apply to Circularity also apply to Cylindricity.

2.0 Definitions

**Actual Profile** – The actual profile is the cross-sectional profile of the part feature.

**Attribute Data** – Attribute data is information obtained from an inspection process that indicates whether a part is acceptable for use.

**Calibration** – Calibration is the act of inspecting and subsequently adjusting a gage, when needed, to meet a specific parameter.

**Certification** – Certification is the act of inspecting a gage to verify that it meets a specific parameter.

**Circularity (roundness)** – Circularity is a condition of a surface where, for a feature other than a sphere, all points of the surface intersected by any plane perpendicular to an axis are equidistant from that axis. For a sphere, all points of the surface intersected by any plane passing through a common center are equidistant from that center.

**Coordinate Measuring Machine (CMM)** – A CMM looks like a milling machine with a hard probe, instead of a cutting tool, which gathers data about a surface being probed or traced. The surface data is then analyzed.

**Cylindricity** – A cylindricity tolerance specifies a tolerance zone bounded by two concentric cylinders within which the surface must lie. In the case of cylindricity, unlike that of circularity, the tolerance applies simultaneously to both circular and longitudinal elements of the entire surface. The cylindricity tolerance is a composite control of form that includes circularity, straightness, and taper of a cylindrical feature.

**Filter** – A filter is an electrical circuit that attenuates the amplitudes of certain undulations of the actual profile.
**Full Indicator Movement (FIM)** – This is the up and down movement of the measuring indicator. It was formerly called Total Indicator Reading (TIR).

**Fixed Limit Gage (limit gage)** - A fixed limit gage is a device of defined geometric form and size used to assess the conformance of a feature(s) of a part to a dimensional specification.

**Fixture** – A fixture is a device used to hold parts securely in the correct position in a tool or gage during manufacturing, assembly, or inspection.

**Functional Fixture** – A functional fixture is a device having integral gage elements that make physical contact with part datum features. It typically holds parts as they would be held when assembled. The fixture and its gage elements represent simulated datum features from the mating part.

**Gage Element** – A gage element is a physical feature of the gage used in the verification of part compliance to the associated tolerance requirement. These physical features represent datum feature simulators or virtual condition boundaries.

**Gagemaker’s Tolerance** – A gagemaker’s tolerance includes the accuracy of the gage, wear allowance, measurement uncertainties, temperature when the gage is used, dust, etc. Generally the unwritten gagemaker’s tolerance is a total of 10%. To reduce rejection of parts, manufacturing needs to stay away from MMC size. e.g. when machining an outside diameter on a lathe, the lathe operator should not machine down to MMC size, as measured with a two point calipers, and quit machining. This MMC size diameter may not pass inspection because the gages are different and there is a possibility of gage error. The lathe operator should machine to near the mean diameter.

**GO Gage** – A GO gage is a fixed limit gage that checks a feature of size for acceptance within maximum material condition perfect form boundary.

**Ideal Roundness** – Ideal roundness is the representation of a planar profile on which all points are equidistant from a center in the plane.

**Least Material Condition (LMC) Size** – LMC is the condition in which a feature of size contains the least amount of material within the stated limits of size. (e.g., maximum hole diameter, minimum shaft diameter).

**RULE:** LMC size is inspected with a two point NOGO gage that will not enter the feature at any cross-section.

**Least Square Circle Center** – It is the center of a circle from which the sum of the squares of the radial ordinates of the measured polar profile has a minimum value. It is established by mathematical analysis of the profile and, in order to be practical, generally requires a computer to calculate it.

**Maximum Inscribed Circle Center** – It is the center of the largest circle that can be inscribed within the measured polar profile. It is also known as the plug-gage center and is sometimes used for internal diameters.
Maximum Material Condition (MMC) Size - MMC is the condition in which a feature of size contains the maximum amount of material within the stated limits of size. (e.g., minimum hole diameter, maximum shaft diameter).

RULE: MMC size is inspected by a full form (3D) GO gage that will enter the feature to the minimum depth stated on the drawing. This GO gage will be MMC size. If the feature is MMC size, a MMC gage will not enter the feature and thus is a bad part. Manufacturing should have a rule to never create a MMC feature because it will be rejected. MMC really means “PERFECT”.

Measured Polar Profile (polar chart) – The measured profile that has been recorded about a center or axis of rotation wherein the central angle of the measured profile features do not differ significantly from those of the circular surface.

Minimum Circumscribed Circle Center – The center of the smallest circle that contains the measured profile. It is also known as the ring-gage center and is sometimes used for external diameters.

Minimum Radial Separation Center – The common center of two concentric circles that contain the profile and have a minimum radial difference. It is also known as the center for minimum full indicator movement and zone circles.

NOGO Gage – A NOGO gage is a fixed limit gage that checks a feature of size for violation of the least material condition actual local size.

Nominal Profile – The intended cross-sectional profile, the extent and shape of which are usually shown and dimensioned on a drawing or descriptive specification.

Out-of-Roundness – The radial deviation of the actual profile from ideal roundness.

Preferred Center – The center from which the out-of-roundness value is determined. It is the minimum radial separation center, unless otherwise specified.

Rule One – Rule One is automatic in the U.S., and is not automatic in ISO countries. Rule One allows inspection to reject bad workmanship. Rule One states that on all rigid features, it must have perfect 3D form at MMC size. Rule One does not control the relationship of one feature to another such as perpendicularity. Rule One is typically not measured by inspection because they are not aware of the rule or, there is no correct measuring equipment. They have a box of gage pins to measure the size of a hole, but these pins only go up to certain size and the pins may not be long enough. To measure external diameters, inspection needs ring gages for all sizes and lengths. Even CMMs are not perfect because they take an arithmetic average when touching the diameter in several places. What can inspection do about Rule One when there are no gages or proper equipment? They must inform engineering that Rule One is not being measured, or that special gages need to be made. This is one reason why we have statistical process control where parts are produced to the mean dimensions. Some companies put a note on the drawing stating, “PERFECT FORM IS REQUIRED AT MMC.”

Undulations – The peaks and valleys of a profile.
**Variable Data** – Variable data is information obtained from an inspection process that indicates the level of acceptability of a part by providing a measured value. Therefore, the level of acceptability is recorded as a numerical value.

### 3.0 Circularity Comments

#### 3.1 How Much Out-of-Round

When specifying a diameter, the maximum out-of-round is shown in Figure 1.

The reason the above example is good, is based on the example shown below being good.

#### 3.2 Bench Centers Measurement

The bench centers method requires that the part have machining centers, typically generated by the lathe. The part to be measured is mounted between two centers of a bench center fixture and then rotated while an indicator measures circularity or cylindricity on the surface. If the surface is within the required tolerance, the part is good. However, if the indicator exceeds the required tolerance, the surface may be still good due to other inherent errors in this inspection method. Such inherent errors are improper alignment of the bench centers and the degrees of the conical angle as well as the hole centers and their conical angle in the part. Also, the part may be bowed. The number of individual circularity measurements along the surface is sufficient to satisfy the inspector that the collected data is good or bad in order to determine the status of the part. A simple drawing of the bench center is shown in Figure 2.
3.3 Diametric Measurement – Diametric measurement is a two-point contact method that detects only an even number of lobes of the same lobe size. Since an odd number of lobes is very common, these measurements are unreliable. Typical inspection equipment used for diametric measurements includes micrometers, calipers, bore gages, air gages, and comparators. See Figures 3 - 5.
3.4 V-block Measurement – The V-block measurement method is a three-point contact on the parts. With an odd number of lobes the 90° and 60° V-blocks do not measure circularity. For cylindricity V-blocks also identify error if the shaft is not straight.
With an even number of lobes, the 60° V-block method will conceal the out-of-roundness condition. See Figure 8.
4.0 Verifying Circularity and Cylindricity Tolerance

The bottom line in measuring circularity and cylindricity is to use the proper inspection equipment for the job. The most common equipment is a radial measurement with ultra-precision spindle as shown in Figures 9 and 10.