A Lesson in Profile Tolerancing for Complex Parts

Profile tolerancing can reduce inspection time and measurement errors while improving accuracy.

Jim Stertz

One of the challenges facing precision manufacturers and their medical device manufacturing partners is the increasing feature complexity of tight-tolerance parts. These complex geometries can result in long inspection and verification times and put even the most sophisticated measurement equipment and processes to the test. In addition, design, manufacturing, and quality engineers are often frustrated by communication errors over these features.

Often, a CAD model, which represents the epitome of design intent, is compromised when it is converted to a conventional, 2-D drawing. Engineering drawings that use linear dimensioning (plus-minus tolerancing) for complex geometries, small arc radii, and short surface features can add time, inaccuracy, and measurement error to inspection and verification activities.

However, an approach called profile tolerancing offers optimal definition of design intent by explicitly defining uniform boundaries around the physical geometry. It is an efficient and effective method for measurement and quality control. Using submicron-level measurement equipment and advanced profile analysis software, properly applied and executed profile tolerancing can significantly reduce inspection time, improve accuracy, and reduce measurement error. Profile tolerancing also improves time to market and ensures that components and assemblies function relative to the design intent.

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A Solid Model

A solid model, such as the one pictured in Figure 1, has typical complex features. These features and the model's small arc radii are used throughout this article to demonstrate profile tolerancing. The small arc radii of this feature are depicted in this solid model format, then in a traditional linear dimensioned drawing, and also in a profile toleranced drawing (see Figures 2–5). Finally, Figure 6 on page 58 depicts the feature after it has been machined, measured by a coordinate measuring machine (CMM), and the derived data points (known collectively as a point cloud) have been entered into a profile tolerancing program, in this case, SmartProfile software from Kotem Technologies.

Many medical device engineering drawings currently use linear dimensioning to define component geometries, locations, interrelations, and the requirements for conformance to the design intent. All engineering drawings must account for the size, form, orientation, and location of all features to ensure manufacturability, measurability, and design intent. Geometric controls per ASME Y14.5 are typically applied to specify dimensional tolerances on engineering drawings and define size, form, orientation, and location of features. Many engineering drawings lack the necessary geometric dimensioning and tolerancing to allow for timely and accurate inspection and verification. Plus-minus tolerancing is typically ambiguous and requires extra time by engineering, programming, machining, and inspection functions to debate and agree on a single conclusion.

Geometric Dimensioning and Tolerancing

Using specifications according to the U.S./International Standard for Geometric Dimensioning and Tolerancing (GD&T) can result in a part different from the designer's intent. The following example from the International Institute of GD&T (Figure 2) shows a shape requiring variation not to exceed an inner and outer boundary of concentric rectangles (25 ± 0.1 mm and 50 ± 0.1 mm). Although the graphic reflects the desired boundaries, it would be incorrect to assume it to be the allowable set of boundaries. The linear tolerancing is negatively influenced by an implied

Figure 1: A solid model generated by CAD. The measurements of this model are compromised when converted to a 2-D drawing.

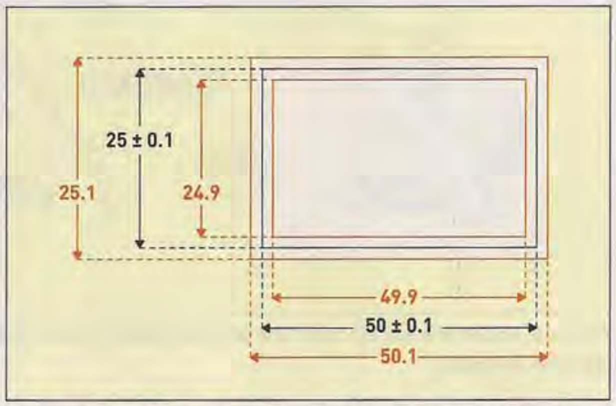

Figure 2. Geometric dimensioning and tolerancing (GD&T) can result in a part different from the designer's intent. Here, a shape requires variation not to exceed an inner and outer boundary of concentric rectangles. Although the drawing reflects the desired boundaries, it would be incorrect to assume it is the allowable set of boundaries.

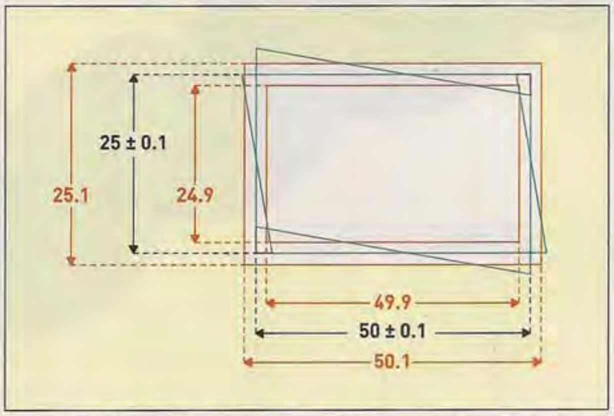

Figure 3. When only a tolerance of size is specified, it does not control the orientation or location relationship between individual features. An individual feature of size can fit within its allowable tolerance of ±0.1 mm, but also fall outside the perceived outer boundary in the opposing direction.

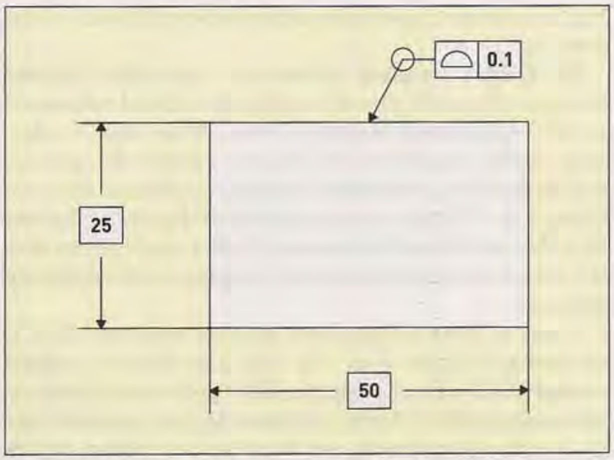

Figure 4. Precision GD&T imparts a profile of a surface control of 0.1 mm all around, which applies to the basic dimensions specified. The design intent is clearly defined and unambiguous.

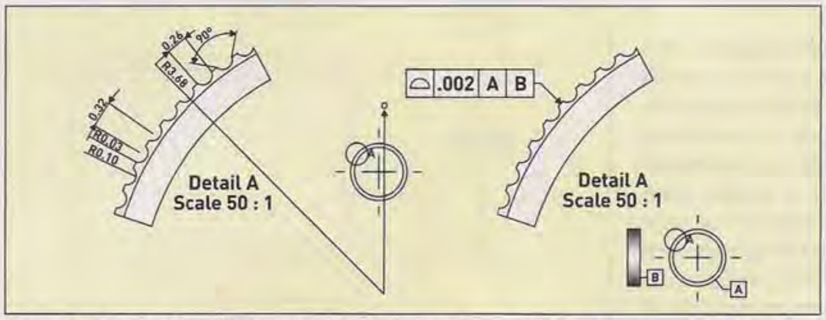

Figure 5. Detail of small arc radii. The left side shows a linear drawing. A profile drawing is on the right.

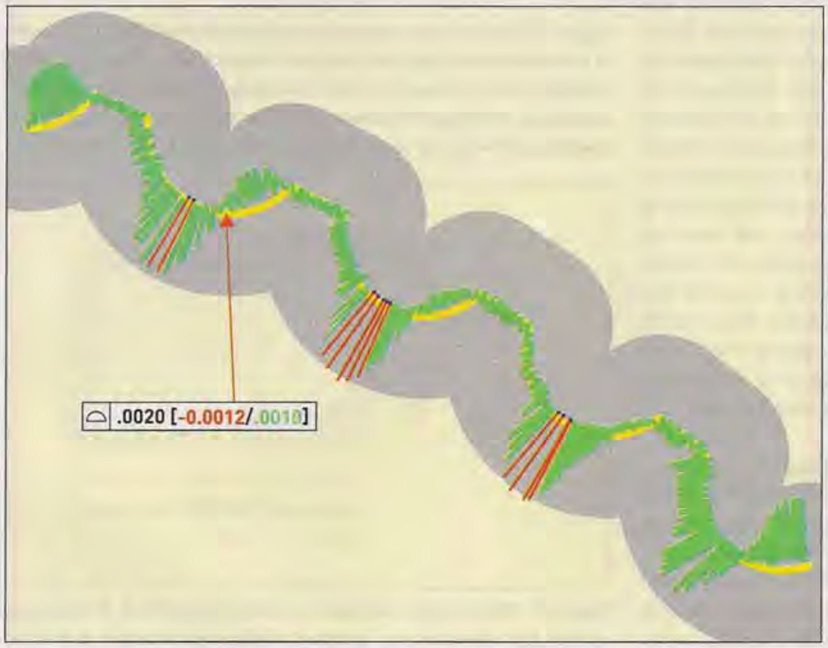

Figure 6. A profile analysis result graphically displays deviations from the CAD model using whisker analysis. Green whiskers show measured points that are within the specified tolerance. The red whiskers show measured points that are out of the specified tolerance.

angular tolerance normally stated in the title block of the drawing.

The GD&T standard defines these particular features (two sets of parallel planes) as dimensioned and toleranced as two independent features of size. When only a tolerance of size is specified, it does not control the orientation or location relationship between individual features. Figure 3 (p. 57) shows that an individual feature of size can fit within its allowable tolerance of ±0.1 mm, but can also fall outside the perceived outer boundary in the opposing direction.

A way to solve this problem is to use precision GD&T, as shown in Figure 4 (p. 57), with a profile of a surface control of 0.1 mm all around, which applies to the basic dimensions specified. Profile tolerance applies perpendicular to the nominal geometry, and its default definition applies bilaterally. That means the tolerance is divided equally (±0.05 mm) around the entire nominal geometry. Therefore, the derived boundary shown in Figure 2 now matches the boundary originally chosen by the designer. None of the undesirable conditions shown in Figure 3 are allowed by this profile tolerance. The result is design intent that can be clearly defined by the designer and unambiguously interpreted by all other supporting technical disciplines.

Engineering drawings with linear dimensioning require the inspection of each feature for size, form, orientation, or location. A single feature can have several inspectable dimensions—and each dimension may also require a different inspection method. An engineering drawing with 20–100 inspectable dimensions can take up to approximately five minutes per dimension per part. This inspection process can be very time-consuming, affecting lead time and adding significant cost.

In addition, for some geometric features, plus-minus tolerancing requires measured points from a CMM to be constructed into geometric shapes to meet the drawing requirements. Small deviations in location with measured points of complex geometries, short surface features, and small arc radii significantly affect the calculated result of geometric shapes. These inaccuracies can lead to acceptance of nonconforming components or rejection of conforming components. Profile tolerancing uses the location of each measured x, y, and z point relative to the CAD model nominal geometry to determine the condition of the measured part or feature.

Profile tolerancing, profile of a surface, and profile of a line can control size, form, orientation, and location simultaneously and replace several linear dimensions. In some applications, a single profile tolerance requirement can replace up to 20 linear dimensions, thereby reducing inspection time from hours to minutes. Profile tolerancing applies a uniform boundary that is equally disposed along the true (theoretically exact) profile. The surface elements of each cross section must be within this boundary. Optimally, the boundary matches the design intent. If these factors are adhered to, then the designer has clearly defined the intent and the results can be unambiguously interpreted by engineering, programming, machining, and inspection functions.

Linear Dimensioning versus Profiling. Figure 5 depicts the detail of the small arc radii using both a linear dimensioned drawing and a drawing using profile tolerancing. The linear dimensioned drawing on the left has more than seven depicted features or dimensions to define the size, form, orientation, and location of the small arc radii and


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A PARTNERSHIP IN PROFILE

A commitment to profile tolerancing is a true partnership between a medical device manufacturer and its supplier. Here are some tips on how to ensure that a supplier is committed to profile tolerancing:

- Has it invested in physical metrology equipment, such as a precision measuring machine, required to measure complex geometries with small deviations?
- Has it acquired profile analysis software needed to analyze the complex surface profiles?
- Is the organization well schooled and trained in GD&T profile tolerancing?

Partnering with a supplier that understands, invests in, and is committed to profile tolerancing can help an OEM achieve communication of design intent that is free of ambiguity.

allows for possible misinterpretation of design intent.

On the right-hand side of Figure 5, the profile drawing uses all of the data points from the original CAD model (see Figure 1 on p. 57), and the small arc radii feature is depicted as a profile of a surface with control of 0.002 in. all around. The simple directions stated in the feature control frame depict all of this information.

Many CMMs, as well as tactile, vision, laser, or white-light interferometers can scan or trace features in 3-D and save the x, y, and z coordinates to a file. Point measurement with a CMM utilizes its strength and minimizes measurement error. This inspection equipment typically has settings for point spacing, points per millimeter, or linear distance per measured point. Hundreds or thousands of points can be taken as a point cloud file and imported into profile analysis software for evaluation of a CAD model.

Profile Analysis Software

Profile analysis software, such as SmartProfile, makes complex profile analysis easy, and SmartProfile is the first automatic software package for profile tolerancing that is compliant with ASME Y14.5/1994 and ISO 1101 standards. SmartProfile imports many common format CAD models as IGES, STEP, or DXF. The CAD features are selected for dimensioning, linear, size, or GD&T, and the tolerances are entered. The program is saved and can be used again, eliminating the need for recreating the program. At this stage, the measured points are imported, a quick alignment is done,

and the points are evaluated. The profile analysis software performs an optimum fit analysis of the measured points to the CAD model. The measured points are translated and rotated until the optimum fit is achieved.

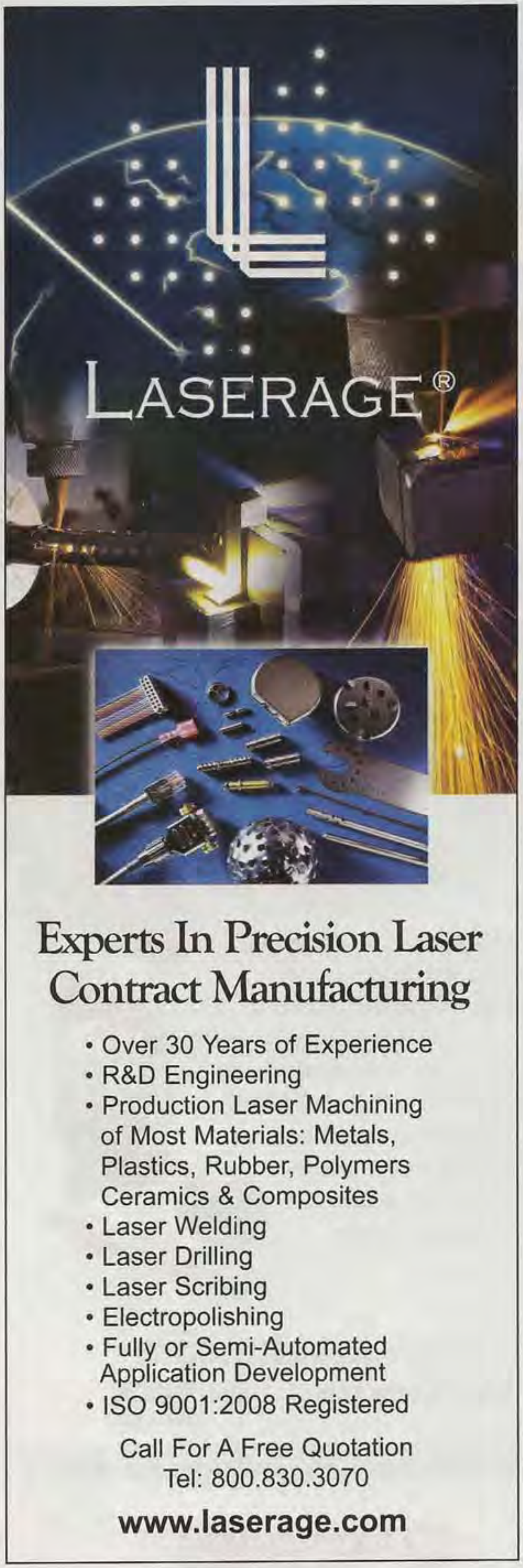
The profile analysis result graphically displays measured point deviations from the CAD model using whisker analysis or a topographical map. This graphical display allows easy visual interpretation of the actual part profile. A viewer can be used by machinists, inspectors, managers, customers, and suppliers to communicate the results of the profile inspection.

Figure 6 on p. 58 shows the simple graphical output from the profile tolerancing software program. The color-coded surface profile uses green whiskers to show measured points that are within the specified tolerance. The length of the whiskers indicates the amount of deviation from the nominal geometry. The red whiskers show the measured points that are out of the specified tolerance. The software supplies a bar graph of the deviation statistics (not shown). The profile analysis results are printed as a hard copy document or saved as a PDF file. Machinists and machine operators who are accustomed to drawings can easily understand and analyze these graphical reports to interpret where process adjustments need to be made. Changes to the machine program or other process variables are made, and then samples are tested again using the previously constructed protocol. Compare this with previous methods using verbal or numerical communication, which are much more difficult, less graphical, and often unclear.

> When design intent is conveyed unambiguously, OEMs don't have to field multiple questions from suppliers as they design a process for manufacturing.

Benefits and Limitations

Profile tolerancing provides benefits for both the supplier and the device manufacturer in terms of product design and inspection. There are several advantages for medical device designers who use position and profile tolerancing instead of linear dimensioning. When design intent is conveyed unambiguously, OEMs don't have to field multiple questions from suppliers as they design and build a process for manufacturing and inspection. Using profile tolerancing tools like SmartProfile software enables parts to be inspected in a shorter time while minimizing measurement error compared with conventional methods. For example, looking at an application on a complex feature for an implantable medical device, inspection using linear dimensioning methods would typically take more than 60 minutes per part. Implementing profile dimensioning methods with this same feature requires less than 10 minutes for inspection, with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improved accuracy. Such time savings, if multiplied over an entire production run, would increase throughput and help to alleviate potential bottlenecks during in-process and finished-goods inspections.

Profile tolerancing optimally represents design intent when the designer is looking for all of the applicable surface geometries to lie within their respective uniform tolerance zones simultaneously. It is essential to know that there are some design applications for which profile tolerancing cannot be used. For example, applications of press-fit pins or thread-in plates are not appropriate. Both of these applications require positioning using a projected tolerance zone for control of the projected axis. Position enables projection of the axis while profile controls the surface.

Barriers to Adoption

An OEM that is poised to embrace profile tolerancing will no doubt run into resistance from those who would prefer the way things have always been done. It is not just internal naysayers, but also suppliers that might fight the change. In addition, the investment for an OEM's suppliers can be steep in terms of training, equipment, and software.

However, the benefits to the supplier organization and its customers are hard to challenge. It would be good for an OEM to contact its current suppliers to measure their knowledge of profile tolerancing and their commitment to this system. Suppliers that aren't properly trained in and equipped for profile tolerancing simply cannot match the OEMs in terms of design intent as quickly or as accurately as a supplier that has fully embraced profile tolerancing. (See the sidebar "A Partnership in Profile" on page 60.)

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Conclusion

Profile tolerancing, when it is applied correctly, provides manufacturing and inspection functions with unambiguously defined tolerancing. Those data are manufacturable and measurable. Customers can see cost and lead time reductions with parts that consistently meet the design intent. Components can function properly—eliminating costly rework, redesign, and missed market opportunities.

OEMs need to ensure that they understand the process before moving to adopt profile tolerancing. They also need to ensure that suppliers have been brought into the process and are able to accommodate use of the software and equipment. ■