# AC 2012-4265: PROMOTING AWARENESS IN MANUFACTURING STUDENTS OF

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# Promoting Awareness in Manufacturing Students of Key Concepts of Lean Design to Improve Manufacturing Quality

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## Abstract:

Lean design is a product design philosophy that aims to drive down resource waste on the factory floor using efficient design. Munro [i] provides data to show that Lean design has the greatest impact on the efficient workings of a manufacturing operation. Lean design influences floor-space, labor, raw material, quality, and ultimately profits for a manufacturing company.

In this paper, how companies can pursue Lean design utilizing geometric dimensioning and tolerancing (GD&T) through target manufacturing and zero tolerancing at the maximum material virtual condition (MMVC) are shown. Although these concepts are available in different places within GD&T and quality texts, the connection eludes some educators and most students. Further, how these concepts can be utilized by manufacturing companies as strategic tools to better communicate between product-design and manufacturing personnel is presented. Why it is important to include the concepts of Lean design in product design and manufacturing engineering curriculum is also explained.

## Key Words:

Lean design, geometric dimensioning and tolerancing (GD&T), goal post tolerancing, zero defects, on target design and manufacturing

## Introduction:

GD&T allows designers to specify maximum available tolerances on product drawings and at the same time maintain component interchangeability. GD&T hence is an important tool for a company that would like to pursue Lean design. Also, GD&T through the use of the concept of zero tolerance at MMVC for an assembled product, further ensures that no good products that will function well in an assembly are rejected because of bad tolerancing practices. Through the use of the concept of zero tolerance at MMVC, GD&T is capable of preventing the best fitting parts to not be rejected. When this happens, it increases the part manufacturing cost and results in waste which can make companies less competitive.

However in utilizing GD&T, parts always need to have bilateral tolerances. This is because GD&T manages product quality using attribute gaging or go/no-go gages, which always end up utilizing the full spectrum of the available manufacturing tolerance. However, as precision assemblies always have tolerances that are unilateral since they are based on limits and fits, GD&T is not useful in controlling specifications on unilaterally toleranced parts. Using the empirical law of statistics, we can change the specifications for the unilateral tolerances and make them bilateral without losing the functionality of the part, thus allowing us to utilize GD&T for bilateral tolerances.

## The Importance of Targeting the Nominal Dimension in Manufacturing:

The importance of utilizing unilateral tolerances in design and manufacturing was demonstrated by two case studies in the real-world. In the first case, U.S. & Japanese contractors were awarded contracts to build F-16s [ii] using the exact same design and drawings. The parts were made to strict specifications. Naturally, as the blue prints used by both were the same, equivalent performance was anticipated from both. But this was not the case when the field history results came in after some use of the jets in the field.

What was found was that the Japanese built planes had a mean-time-between-failure (MTBF) reliability that was twice as that of the U.S. F-16's! Such a difference in performance cannot be attributed purely to chance. There has to be an uncommon cause that resulted in this. On conducting an analysis, it was found that the U.S. manufacturers used the full spectrum of tolerance that was available to them, whereas the Japanese parts were virtually identical with dimensions at their nominal, target or basic sizes.

The two lessons that were learned from this experience were that the target dimension variation plays a key role in determining the quality of parts, and variation in manufacturing components has an inverse correlation to reliability in the field.

In another well-documented case study between Ford and Mazda [iii], Ford contracted Mazda to make front-wheel-drive automatic transmissions. The parts were made by Ford at its Batavia plant in Ohio. Ford issued the exact same blueprints to Mazda, who planned to build the transmissions in Japan. When the transmissions were built into cars and had a considerable run on the roads, it was found that the transmissions made by Mazda had a substantially lower warranty claim rate than the ones made by Ford.

Ford investigated and found that their plant in Ohio utilized 70% of the tolerance spread available, whereas Mazda used only 27% around the target. It was found that Ford's parts were very good but Mazda's were superior. Mazda's parts were all more nearly like one another and close to the target value that the designer had in mind.

One other finding from the investigation was that Mazda was using a slightly more expensive and complex grinder to finish the valve outer diameters. This increased Mazda's manufacturing cost a little, but taking the warranty cost into account, the overall cost was much lower!

As a result of the analysis [iv], the then Chairman of Ford Donald Peterson issued an edict to Ford engineers that they should design to a target value and not hide behind broad specification limits. Also, it can be fathomed that this lesson was conveyed to the manufacturing shop floor that when a target dimension has been specified by design, they should aim to get as close to it as possible, and not convert it into a bilateral or goal-post tolerance.

### Specifying Manufacturing Tolerances for Precision Assemblies:

For precision assemblies, tolerancing is always unilateral since it is based on limits and fits, and with a definite fit in mind, a designer ends up creating unilateral tolerances for a shaft and hole as shown in Figure 1. Here, we see that the nominal hole-diameter that the designer intends to use is 1.000” with a clearance of 0.005” between the hole and the shaft. Based on manufacturing tolerances of 0.003” for the hole and 0.002” for the shaft, the dimensions that a designer would specify on the hole will be 1.000” (+0.003 / -0.000) and for the shaft will be 0.995” (+0.000 / -0.002) as shown in Figure 1.

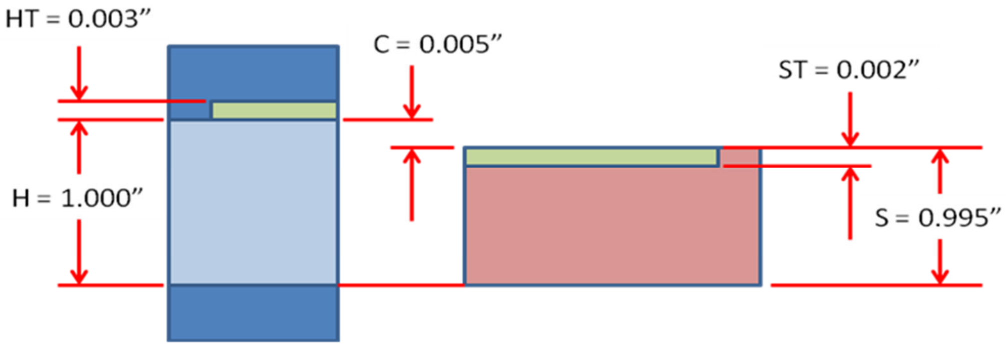

**Figure 1. Precision Assembly between a Hole and a Shaft [v]**

Now for producing the hole with a target dimension of 1.000”, if the manufacturing machine is set at 1.000”, although a majority of the parts based on the normal curve will have a dimension close to 1.000”, half the parts will have a dimension greater than 1.000” and half will have a dimension less than 1.000”. In other words, although half the parts produced will be as close to the nominal or target dimension of 1.000” as possible, half will be out of tolerance with a dimension below 1.000”. This definitely is not acceptable.

To counter this, it is recommended to use the standard deviation of the machine producing the dimension, to come up with the dimension that should be targeted during the manufacturing operation. A general rule of thumb is to see if we can use a machine with a standard deviation of less than one-twelfth the tolerance spread. Considering the tolerance spread for the hole is 0.003”, a machine with a standard deviation of 0.003” / 12 = 0.00025” should be sought. Say we have selected a good machine for with a standard deviation of 0.00017” to perform the hole making operation.

The Empirical rule of statistics tells us that 99.7% of the normal curve will lie between mean minus 3 times the standard deviation, and mean plus 3 times the standard deviation. In other words, 99.7% of a normally distributed data set will lie between a specification limit of 6 times the standard deviation, with the mean at the center of the specification limit.

With the standard deviation of the process being 0.00017”, we can aim the dimension to be targeted during manufacturing of the 1.000” hole at 1.000” + 3 x (0.00017”) = 1.0005” as shown in Figure 2. This would be much better than the 1.0015” that we would have targeted had we used the entire available spread as the specification tolerance and variation for the process.

Hence, using the Empirical law of statistics students should be taught how specifications that have a unilateral tolerance should be converted into a bilateral tolerance without losing the functionality of the part. This is important in adapting GD&T as a communication tool between product design and manufacturing to achieve the best quality at the minimum cost.

It is worth noting here that the importance of unilateral tolerances, the concept of converting unilateral tolerances into bilateral tolerances to which many manufacturing personnel on the shop floor are comfortable with, and the use of GD&T as a tool to get a strategic advantage in design and manufacturing is missing in many manufacturing curriculum, and it behooves us as manufacturing faculty to promote and teach these concepts to future manufacturing engineers and technologists.

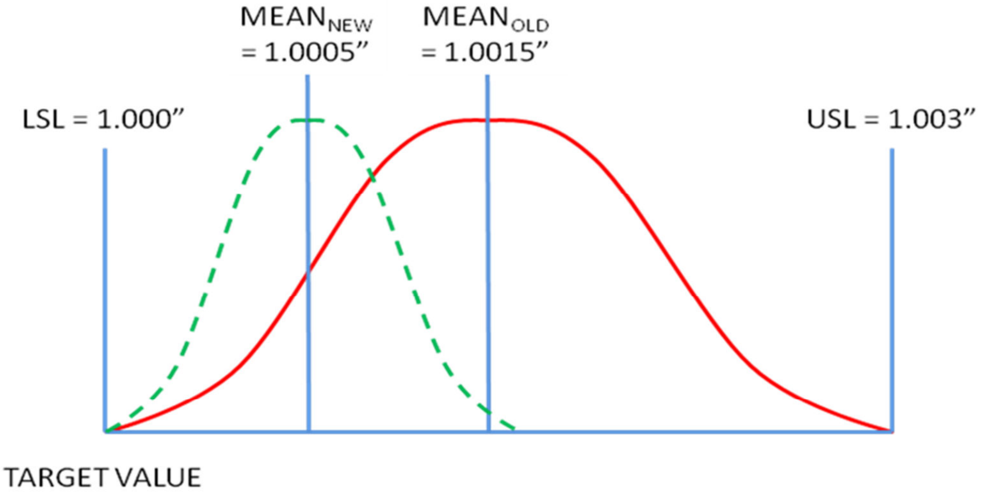

**Figure 2. Aiming as Close to the Target Value as Possible [vi]**

## Using GD&T as a Strategic Manufacturing Tool:

After discussing the concept of how to seek out a target tolerance for manufacturing based on the standard deviation of the process, let us now discuss the other core concept that manufacturing engineers and technologists of tomorrow need to be aware of, which is GD&T applied with zero tolerancing.

The goal of GD&T is to allow components in assembly to enjoy the maximum amount of tolerance possible without undermining the functionality of the product. In achieving this, GD&T requires the specification of a tolerance at the maximum material condition as shown in Figure 3. This is a component drawing for a small metal plate with a hole in the center.

The dimension of the plate is 2.5" by 1.5", with a hole in the center of diameter 0.5". The tolerance on the dimensions of the plate is ±0.005", with the tolerance on the 0.500" hole as ±0.004". The geometric tolerance frame below the Ø0.500" hole requires the entire axis of the hole to lie within a tolerance zone of Ø0.003". The center of the tolerance zone will be positioned with respect to the three datums A, B, and C such that it will be perpendicular to the face A, 0.750" away from face B, and 1.250" away from face C.

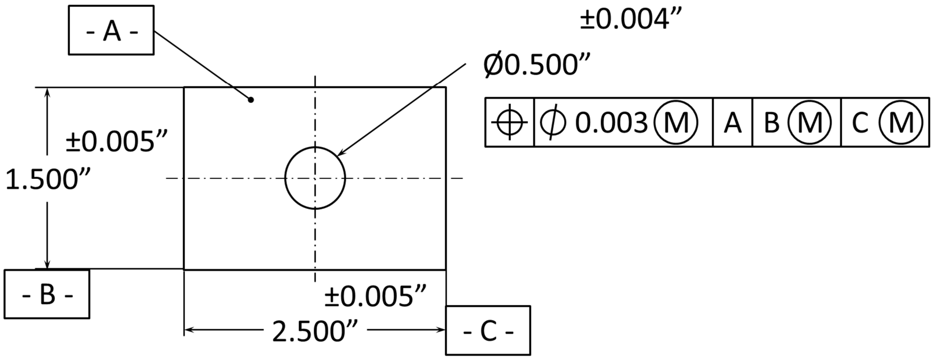

**Figure 3. Engineering Drawing for a Plate with GD&T Requirements**

Now if the plate is made within the tolerances, it will work fine. Now say the outside dimensions of the plate have been manufactured at 1.495" x 2.495", with the hole-size in the center at 0.504" (the least material condition for all dimensions as per the drawing). Further let us assume that the position tolerancing for the center hole is at a diameter of 0.003", and the part is not fitting in place during assembly.

In such a case, the normal practice that has been adopted in manufacturing since ages is to make the center hole larger so that additional clearance is made available for assembly to happen. Several plates can be salvaged this way, but not without the requirement for issuing a tolerance discrepancy waiver on the shop floor from a manufacturing engineer or manager. This results in unnecessary lost effort which is not required in the first place.

To counter this, ISO 1101:2004 [vii] standards have come up with what they call the "reciprocal" requirement where the tolerance available for the dimension of the hole and the positioning of the hole is merged together, and manufacturing personnel is allowed to use the size tolerance for geometrical tolerance and vice-versa if need be. A drawing with such a reciprocal requirement for the plate shown in Figure 3 is shown in Figure 4.

What the reciprocal requirement essentially means is that of the positional tolerance of 0.003" that is not used in defining the position of the axis of the hole, can be utilized by the hole size of the 0.500" hole, and vice versa, what size tolerance from the ±0.004" size tolerance is not utilized by the hole can be used for defining the position of the hole.

The drawing suggests that if the hole-size is at the MMC of the hole which is 0.500" – 0.004" = 0.496", the hole can be off the ideal position by 0.003". Now if assembly is still not possible, we can make the hole-size larger by 0.003" and the part will assemble.

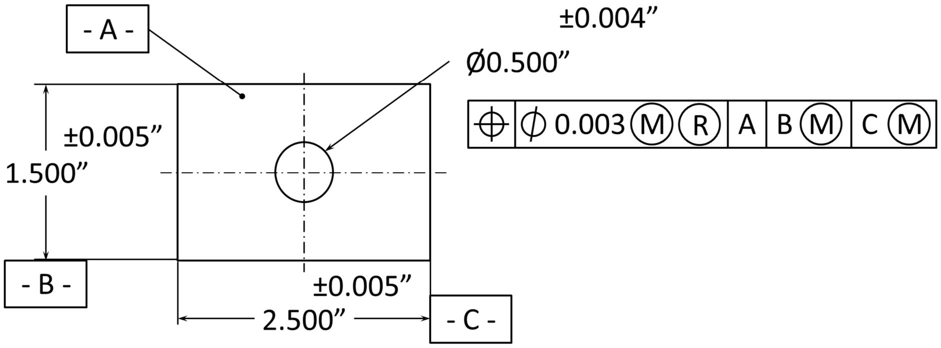

**Figure 4. Engineering Drawing with Reciprocal Requirement as per ISO 1101:2004**

ANSI Y-14.5 – 2009, which is the American Standard on GD&T, does not have a provision for a reciprocal requirement. However, we can achieve this for the drawing shown in Figure 3, by utilizing the GD&T frame as shown in Figure 5.

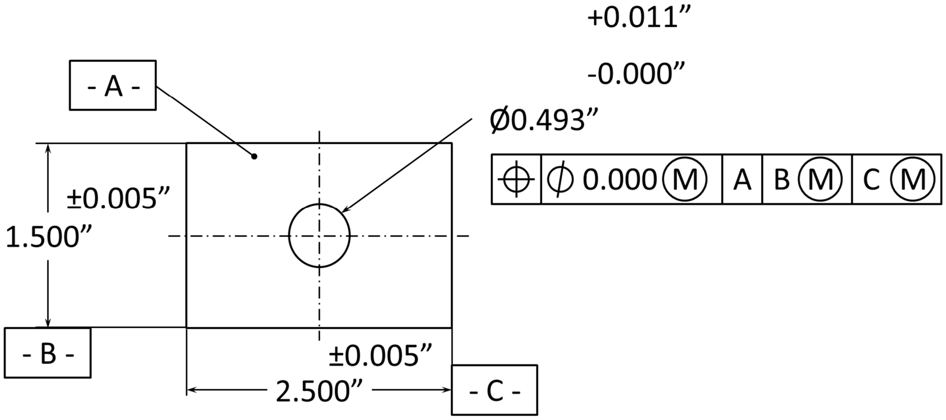

**Figure 5. Engineering Drawing with Zero Tolerance at MMC as per ANSI Y-14.5 – 2009**

The diameter to be specified for the 0.500” nominal hole on the drawing is derived by taking the MMC for the hole of 0.500” – 0.004” = 0.496”, and subtracting from it the positional geometrical tolerance of 0.003”. The resulting dimension is called the maximum material virtual condition (MMVC) for the hole, which is 0.496” – 0.003” = 0.493”. In no circumstances the hole-size can go below this dimension, and hence if the designer is attempting to pass a dowel or a bolt through this hole, it will have to have a size below that dimension.

Now, the maximum size the hole may have as per the old drawing (Figure 3) is 0.500” + 0.004” = 0.504”. As the minimum hole-diameter that we derived above is 0.493”, this gives the tolerance for the hole as 0.504” – 0.493” = 0.011”. Hence, the hole-size that should be specified on the drawing with the position tolerance as zero at MMC is 0.493” (+0.011” / -0.000”).

This concept needs to be clearly understood by manufacturing technologists and engineers as many manufacturing personnel think that specifying a zero tolerance on a drawing is asking for perfect parts, which is impossible. To reemphasize, the total position tolerance available when the hole is at the MMVC, and the datums are at the MMC, will be zero as shown in Figure 6. However, this will seldom happen, as during manufacturing it is not possible to target the MMC of the dimension sought as demonstrated above or else half the parts produced will be rejected. Hence, in any manufacturing scenario, there will be ample tolerance available for the positioning of the hole.

| | | | Datum B | | Datum C | | Total Position Tolerance Available (ø) |
|---|---|---|---|---|---|---|---|
| Diameter of Hole | | Position Tolerance Available (ø) | Dimension | Position Tolerance Available | Dimension | Position Tolerance Available | |
| MMVC | 0.493" | 0.000" | 1.505" (MMC) | 0.000" | 2.505" (MMC) | 0.000" | 0.000" |
| MMC | 0.496" | 0.003" | 1.505" (MMC) | 0.000" | 2.505" (MMC) | 0.000" | 0.003" |
| Nominal | 0.500" | 0.007" | 1.500" (Nominal) | 0.005" | 2.500" (Nominal) | 0.005" | 0.017" |
| LMC | 0.504" | 0.011" | 1.495" (LMC) | 0.010" | 2.495" (LMC) | 0.010" | 0.031" |

**Figure 6. Bonus Tolerances that can be expected as per ANSI Y-14.5 – 2009**

As the dimensions of the hole and datums B and C move from the MMVC to the LMC, 0.011” will be available from the positional tolerance for the hole, and 0.010” will be available from each of the datums for a total tolerance of 0.031” as shown on the last row in Figure 6. The goal of providing zero tolerancing is that if the dimensions on the part exceed the allowable tolerances provided, there is no need for asking the design engineer for a discrepancy waiver, as all the tolerance that can be provided by the designer has been provided on the print, and if the part is not within those tolerances, it needs to be rejected.

## Conclusions:

Although the ideas mentioned in this paper are good manufacturing practices that manufacturing personnel should be implementing to uphold the quality leadership of American manufacturing, they are seldom stressed and are incorrectly practiced. Manufacturing technologists and engineers need to be taught these concepts so that they begin to promote the importance of achieving manufacturing dimensions as close to the target dimension specified by design engineers as possible. This is the only way we will be able to match the quality exhibited by Japanese and other upcoming global manufacturers.

Further, utilizing the standard deviation to derive the dimension that manufacturing personnel should target should be promoted. In doing so though, good machines which are at least capable of holding the standard deviation of the dimension being produced to less than one-twelfths the specification spread should be utilized.

GD&T has the potential of bringing down costs through the use of attribute gaging which takes substantially less time to implement than variable gaging. However, the use of GD&T promotes the use of the total tolerance spread, compromising product quality. Through the use of statistics, students need to be taught how to convert unilateral tolerances into bilateral tolerances using the standard deviation of the process, to get an equivalent quality outcome.

Further, manufacturing personnel should be taught the importance of zero tolerancing at the MMVC, to allow them to get the maximum allowable tolerance, and at the same time reduce the need to seek special variation acceptance when the part has not been made to the specified tolerance.

Our manufacturing engineers, technologists and managers, should be thoroughly taught these concepts so that they can promote these ideas to front line manufacturing people on the shop floor to achieve world-class manufacturing quality levels.

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