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Tolerance analysis and synthesis plays a vital role in the success of a product design because it directly affects product quality and manufacturing cost. It also affects manufacturing process selection and planning. This research provides a review of several commonly used assembly tolerance analysis models and evaluation of their limitations. A new assembly tolerance analysis model is proposed based on process capability indices, mean shifts and tolerance specifications which can be used to bridge the gap between design and manufacturing.

A computer tolerance analysis system that integrates the proposed tolerance analysis model as well as several other assembly tolerance analysis models with a parametric CAD package and a manufacturing process database is described. This system can aid the user to perform tolerance analysis and design concurrently with CAD modeling, and discover potential manufacturing and assembly problems at the design stage. The integration of various modules of the system involves dynamic data exchange(DDE) and object linking and embedding(OLE) under Windows environment. The system allows determination of tolerances on critical assembly dimensions and updating of CAD drawing. Furthermore, allocation of part dimension tolerances may be performed by making use of the data on various manufacturing process capabilities. Examples are presented to explain the use of the developed model and the tolerance analysis system.

# An Integrated Assembly Tolerance Analysis System

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DISK 1: ToleNet v1.0 Program.

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$\sigma_{p,i}$ = standard deviation of process spread for the process used to utilize the dimension of part i.

$\sigma'$ = an equivalent standard deviation for process spread distribution. $\sigma' = E(X-\mu_T)$.

$t_i$ = natural tolerance of the process used to utilize the dimension of part i.

$T_{assem}$ = assembly dimension tolerance.

$T_i$ = dimension tolerance for part i.

USL = upper specification of dimension tolerance.

V(y) = variance of y.

y = value of assembly dimensions as function of individual part dimensions.

Z = number of standard deviations desired for the specified assembly tolerance.

$Z_i$ = number of standard deviations of dimension tolerance distribution for part i.

# An Integrated Assembly Tolerance Analysis System

## Chapter 1 Introduction

In a competitive economy, continuous quality improvement and cost reduction are necessary for any business to remain competitive. The quest for quality and low cost has focused attention on the factors that affect cost and performance of manufactured products, which has led to increasing interest in tolerance design in product development and production.

### 1.1 Motivation and Problem Statement

A product performs best when all parameters of the product are at their ideal values. However, variation of parameters from the ideal values is inevitable because of manufacturing conditions and other factors affecting the product life cycle. Thus, at the design stage all specifications of product parameters are stated in terms of ideal values and tolerances around these ideal values. The product designer must determine proper tolerances for the individual part, as well as the correct amount of clearance or interference between parts to allow proper functioning of assembly.

#### 1.1.1 Tolerance Problem in Design and Manufacturing

Both design and manufacturing engineers are concerned with the magnitude of tolerances specified on engineering drawings. But they often see the problem differently. The design engineer knows that tolerance accumulation controls the critical clearances and interferences in a design, such as lubrication paths or bearing mounts, and thus affects performance. The manufacturing engineer understands that tight tolerances increase the cost and the difficulty of production. Tolerances also greatly influence the selection of production processes and determine the assemblability of the final product. Design engineers often assign tolerances based on the allowable variability in part dimensions in order to meet the required performance functions, but frequently arbitrarily or based on insufficient data or deficient models. Any resulting problems are left to be corrected as they arise during manufacturing planning, tooling, and production. Manufacturing engineers want the tolerances assigned on the drawings to be easily realizable using available facilities and processes, and they want to be sure that current process quality levels do meet the requirements of designed parts. It is not uncommon to see that manufactured parts do not assemble well. Yet the problem can not be easily addressed as to whether it is because of improper design or it is due to inadequate process planning and controlling.

Apparently tolerance analysis and design are an important link between design and manufacturing. It can become a common ground on which an interface can be built between the two. Such a common ground must be based on the fact that since each geometric dimension is realized through manufacturing processes, the determination of each part tolerance is confounded with its manufacturability, manufacturing process capability and production cost. The determination of part tolerance specifications must take into account the natural variation of the manufacturing process in addition to meeting assembly design specifications. An assembly tolerance analysis model based on the actual behavior of manufacturing processes used for processing the parts of the assembly is essential for designing successful assemblies.

As the mechanical product development process advances toward the concurrency to achieve both quality and productivity, tolerance design is most important in leading design to manufacturing and product cost control. Tolerance design serves as a bridge linking design to manufacturing as shown in Figure 1.1.

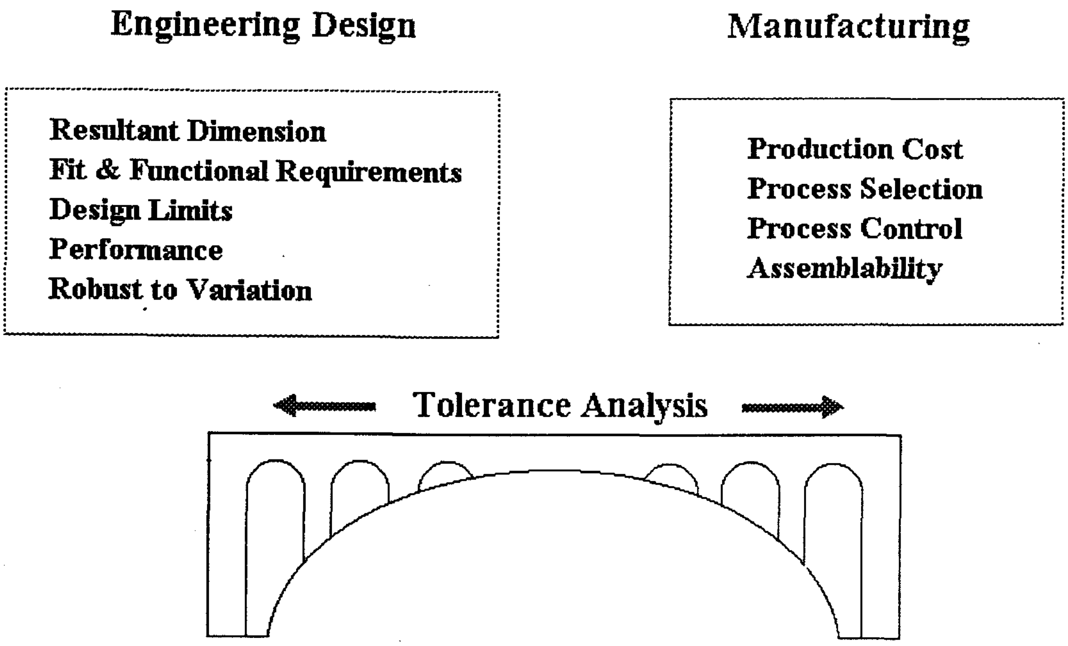



**Figure 1.1 Tolerance Analysis is the Bridge Linking Design and Manufacturing**

### 1.1.2 Linear and Nonlinear Tolerance Analysis Problems

In general, an assembly equation is a function of the form :

$$y = f(x_1, x_2, \ldots, x_n) \qquad 1.1$$

where $x_i$'s are part dimensions and y is the resultant assembly dimension. Unless stated to the contrary, it is assumed that $x_i$'s are scaler and statistically independent random variables.

If equation 1.1 is linear, the mean of assembly dimension y may be determined by calculating the expected value of y, E(y), and the variance of y, V(y), given by equations 1.2 and 1.3.

$$E(y) = \frac{\partial f}{\partial x_1}E(x_1) + \frac{\partial f}{\partial_2}E(x_2) + \ldots + \frac{\partial f}{\partial x_n}E(x_n) \qquad 1.2$$

$$V(y) = (\frac{\partial f}{\partial x_1})^2 V(x_1) + (\frac{\partial f}{\partial x_2})^2 V(x_2) + \ldots + (\frac{\partial f}{\partial x_n})^2 V(x_n) \qquad 1.3$$

The partial derivatives in equations 1.2 and 1.3 represent the sensitivity of the assembly tolerance to component tolerances. They should be evaluated at the tolerance zone midpoints.

When equation 1.1 is nonlinear, the analysis of the tolerance problem is much more complex. Several techniques can be used for estimating the statistical moments of assembly dimension y [Evans, 1975]. The most commonly used method is to expand equation 1.1 using Taylor's series, the order of expansion depending on the desired level of accuracy.

$$\Delta y = \sum \frac{\partial f}{\partial x_i}\Delta x_i + \frac{1}{2}\sum\sum \frac{\partial^2 f}{\partial x_i \partial x_j}\Delta x_i \Delta x_j + \ldots \qquad 1.4$$

In this research, only linear assembly tolerancing problem is addressed. However, the same mechanism of tolerance analysis may be applied to nonlinear problem, though a more complicated method must be employed to predict the summation of dimensions of parts in the assembly.

### 1.1.3 Tolerance Analysis versus Tolerance Allocation

Tighter tolerances on part dimensions and other geometric features help to achieve better assembly quality, while it generally involves higher degree of difficulty of manufacturing and logically higher production cost. Therefore, tolerance design process involves a tradeoff between tighter tolerance for better assembly quality and looser tolerance for easier manufacturing and lower production cost.

In practice, tolerance design has two aspects: (1) tolerance allocation or synthesis - determine the part tolerance given assembly design requirements; and (2) tolerance analysis or control --- verify the desired design requirements, given data concerning individual part dimensions in the assembly. The two procedures are performed iteratively during the design process in order to assure proper assignment of part tolerances without violating the assembly design requirements, while the largest possible part tolerance range is achieved.

In this research, only the tolerance analysis problem is addressed. However, tolerance analysis should not only determine if the given tolerance specifications are adequate, but also give an engineer guidance as to where the tolerance specifications must be made tighter and where the specifications can be relaxed. Therefore, in practice, tolerance analysis problem is not separable from the tolerance allocation problem.

### 1.1.4 Computer Aided Tolerancing

It is natural that computers have been used to assist in solving tolerancing problems [Cox, 1979, Mohammad, 1991]. However, it is not until recently that computer tolerancing has been brought to the level where it can play a key role in an integrated product development system. More people are realizing the importance of tolerance problem as it affects the quality and manufacturability of products and the cost of production[Chase, 1988, Parkinson, 1991]. At such a broad scale, it is impossible to solve tolerancing problems without the help of computers. Computer aided tolerancing is no longer used only for assisting computations in tolerancing problems but also to form a design environment in which problems concerning tolerances can be addressed.

## 1.2 Objectives and Proposed Solutions

The objective of this research is to develop a tolerance analysis model for evaluating critical assembly dimensions and to link tolerance assignments with process behavior so that design and manufacturing may be integrated. Also, this model will provide guidance for process control on the basis of desired assembly yield.

To simplify the problem, the scope of this research is limited to: (1) dimensional tolerances, and (2) linear assembly tolerancing problem. However, the results of this research may be applicable to nonlinear assembly problems, and similar approaches can be applied to study geometrical tolerances.

The proposed approach to develop a new assembly tolerance analysis model is based on two key factors in process control: process capability and process mean shift, so that part dimensional tolerance may be directly related to process behavior. Such a model is expected to provide more realistic results than existing models.

In order to allow tolerance analysis to be performed in direct connection with CAD modeling and a manufacturing database, the mechanism of integration of a tolerance analysis module to CAD and a manufacturing database has been carefully examined, and implemented under Microsoft Windows with data sharing between different program tasks via dynamic data exchange(DDE) and object linking and embedding(OLE).

## 1.3 Overview of Thesis

The development work presented in this thesis includes five sections: Chapter 2: Review of tolerance analysis models and their computer applications; Chapter 3: Development of a new assembly tolerance analysis model; Chapter 4: Development of an assembly tolerance analysis system. Chapter 5: Using the Developed System. Chapter 6: Conclusions and Recommendations. Two appendices are included: Appendix A includes derivation of the relationship between two dynamic process capability indices and a proposed mean shift factor; a user's guide for reference on how to use ToleNet program is included in Appendix B. The compiled program and necessary files to run the presented examples are included in attached Disk 1. The detailed Visual Basic codes of the program are included in attached Disk 2.

# Chapter 2 Review of Tolerance Analysis Models and Their Computer Applications

For most mechanical products, product performance degrades as some of the critical dimensions such as clearances and interferences deviate from ideal values. A critical dimension in a mechanical assembly is usually a function of some part dimensions and geometric shapes. The deviation of a critical dimension is determined by the deviations on both part dimensions and shapes. To assure a functional assembly of imperfect parts, it is necessary to specify tolerances which define limits of size and shape, namely dimensional and geometrical tolerances.

The most popular or standard specification for dimensional tolerance is high/low tolerancing, denoted as $^{+\text{ high tolerance}}_{-\text{ low tolerance}}$. The high and low tolerances need not be equal to form a symmetrical tolerance zone. However, in this thesis, only symmetrical tolerance specification, $\pm$tolerance, is used. Any non-symmetrical tolerance specification can easily be transformed into symmetrical form.

In statistical tolerancing, specifying a tolerance on a dimension is the same as specifying a distribution for the dimension. After the distribution on each independent dimension variable has been specified, different techniques can be utilized for analyzing the response of a dependant assembly dimension.

Research has been carried out to develop both statistical and deterministic tolerance analysis techniques. Statistical techniques can be classified as: (1) Extended Taylor series method, (2) Numerical iteration method, and (3) Monte Carlo simulation method [Evans, 1975], and (4) Taguchi method [Taguchi, 1978, D'Errico, 1988]. The "variational geometry" method, advocated by Hillyard [Hillyard, 1978], is a widely accepted deterministic technique. Due to their complexity and general adaptability, these techniques are often called advanced tolerance analysis methods. These advanced techniques give the most accurate results in estimating the response of the dependant assembly dimension when the independent dimensions have various statistical distributions and the assembly function in general is non-linear. However, they can only be applied when: first, the distributions of the independent dimensions are well studied; and second, the factors affecting production process output are well known and can be measured or described mathematically. The information on the development of advanced tolerance analysis techniques can be found in the references [Turner, 1991 and 1987, Shah, 1989, Suvajit, 1991, Astephen, 1990, Lee, 1990, Peter, 1992, and Porchet, 1992].

At the product design stage and even at the production stage, the above mentioned data usually are not available until the studies are carried out during production, if it is planned to do so. Therefore, advanced tolerance analysis techniques give little help in product design and in leading design to manufacturing.

In practice, the most commonly used tolerance analysis techniques are the so-called simple tolerance analysis methods or models. These techniques are used when the advanced methods cannot be applied because of the unavailability of required data or the complexity of the technique. They are based on intuitive assumptions on how the independent part dimensions in the assembly are distributed and how they will accumulate. A number of these simple tolerance analysis models exist with different levels of sophistication. Some of these simple tolerance analysis models and their computer applications are reviewed below.

## 2.1 Background of Tolerance Analysis

### 2.1.1 Assembly Fundamental Equation and Sum Dimension

The basis for rational tolerance specification is to create an analytical model to predict the accumulation of tolerances in a mechanical assembly. From assembly equation 1.1, the assembly dimension can be predicted if every independent dimension can be determined, and the tolerance on assembly dimension can be predicted if the tolerance on independent dimensions can be determined by using equation 1.4.

When assembly equation 1.1 is linear, the expected value of assembly dimension is given by equation 1.2, or in the more frequently used form

$$y = \sum X_i \qquad 2.1$$

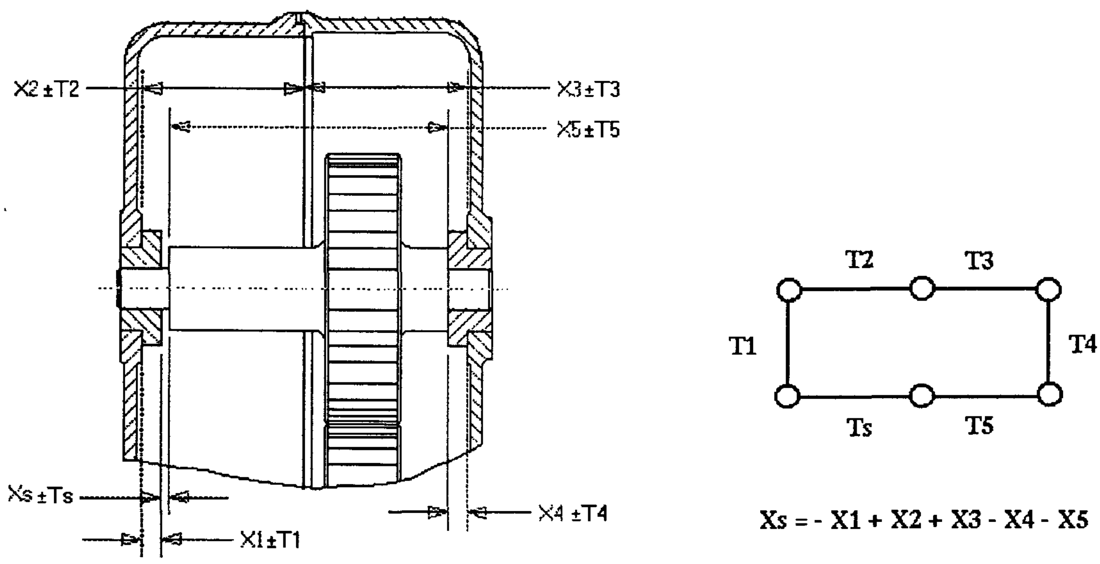
where y is the expected value of the assembly dimension and $X_i$'s are independent part dimensions, and the derivatives are assumed to be one for simplicity of expression. In cases where these derivatives have values other than one, they can be added accordingly. Equation 2.1 is also often called assembly fundamental equation [Bjorke, 1989].

The tolerance of assembly dimension is the square root of the variances of the assembly dimensions given by equation 1.3 or in a more frequently used form with the same simplification as equation 2.1

In the following part of the thesis, all the derivatives are also omitted for simplicity. However, in practice, if the derivatives are not equal to one then they should be added accordingly.

## 2.1.2 Tolerance Chain

A tolerance chain is based on manual techniques developed at the start of the century. Viewing tolerances as "small" deviations in dimension variables, the tolerance chain method represents the relation of linear summation of part tolerances as a geometrical "chain". A chain is a sequence of elements such that each element in the sequence has one endpoint in common with its predecessor in the sequence and its other endpoint in common with its successor in the sequence. The interconnection between links in a tolerance chain is given by the fundamental equation 2.1. To view each dimension as the vector in the space span, the summation of chain links describes the performance of dependant dimension to the variation of independent dimensions. The geometric meaning of chain links is explained in Figure 2.1. A tolerance chain considers only the dimension of the part and does not describe the geometric feature of the part as shape, orientation, etc.




$$Xs = - X1 + X2 + X3 - X4 - X5$$

**Figure 2.1 Tolerance Chain**

In this thesis, tolerance chain is only used to help visualize the mating relationship between the part dimensions in an assembly.

## 2.2 Existing Assembly Tolerance Analysis Models

The most common tolerance analysis models for predicting the sum of part tolerances in an assembly (or a critical assembly dimension) are the Worst Case(WC) and the Root Sum Squares(RSS) models [Fortini, 1967, Spotts, 1978].

**Worst Case Model:**

$$T_{assem} \leq \Sigma T_i \qquad 2.2$$

where $T_{assem}$ is the sum tolerance on the assembly and $T_i$ is tolerance for part i.

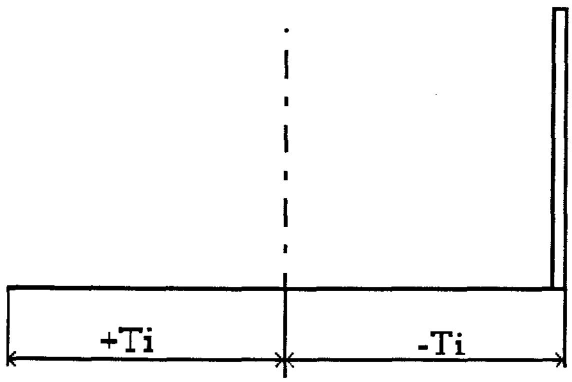
**Root Sum Squares Model:**

$$T_{assem} \leq \sqrt{\Sigma T_i^2} \qquad 2.3$$

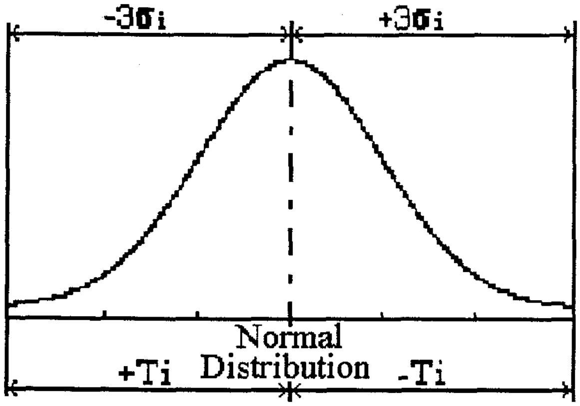
The Worst Case model makes no assumptions about dimension distribution within the tolerance specification range. It only states that no parts should fall outside the tolerance range and all the dimensions are assumed to be located at the limit of the tolerance specification, resulting in a worst case of the assembly dimension (Figure 2.2). As the number of parts in the assembly increase, part tolerances must be greatly decreased in order to meet the assembly tolerance limit, resulting in higher production costs.

In the Root Sum Squares model the dimensions of all parts are assumed to be normally distributed with the mean at the tolerance specification midpoint. Tolerances are commonly assumed to correspond to six standard deviations ($6\sigma$, or $\pm 3\sigma$ for high and low tolerance specification). When the tolerance limits are at $\pm 3\sigma$, there are 2.7 parts per one thousand out-of-tolerance, and likewise the resulting assemblies will have 2.7 parts per one thousand out-of-tolerance. This corresponds to an acceptance rate of 99.73 percent. Compared with the Worst Case model, part tolerances in the Root Sum Squares model may be increased significantly, because they add as the root sum squares.

While the Worst Case model is too conservative, the Root Sum Squares model generally predicts too few rejects compared with real assembly processes. This is due to the fact that the normal distribution is only an approximation of the true distribution which may be flatter or skewed. The mean of the distribution may also be shifted from




(a). WC Model: Part dimension assumed at tolerance limit




(b). RSS Model: Part dimension normally distributed with mean at nominal value

**Figure 2.2 Part Dimension Distribution of the Worst Case and the Root Sum Squares Models**

the midpoint of the tolerance range. To account for these uncertainties, a more general form of the Root Sum Squares model is used:

$$T_{assem} \leq C_f \, Z \sqrt{\Sigma(\frac{T_i}{Z_i})^2} \qquad 2.4$$

where Z is the number of standard deviations desired for the specified assembly tolerance and $Z_i$ describes the expected standard deviations for each part tolerance; $C_f$ is a correction factor added to account for any non-ideal conditions. Typical values for $C_f$ range from 1.4 to 1.8 [Bender, 1968, Wolff, 1961]. As there is no physical significance connected to how $C_f$ is valued, it is similar to a safety factor and is not preferred for quality improvement use.

**Example 2.1:**

Consider a classical example of a stack of n disks. Assume that the disks are 30 mm in diameter and 3 mm thick (Figure 2.3). Suppose that n = 10 and the desired stack height is 30±0.20 mm. Determine the disk thickness tolerance.

Using the Worst Case model:

$$T_d = T_{assem}/10 = 0.20/10 = 0.02 \text{ mm.}$$

Using the Root Sum Squares model:

$$T_d = T_{assem}/\sqrt{10} = 0.20/\sqrt{10} = 0.06 \text{ mm.}$$

According to the Root Sum Squares model, when the disk thickness tolerance is ±0.06 mm, the stack height tolerance will be ±0.20 mm with only 0.27% assemblies outside the tolerance specification. The disk thickness tolerance calculated by the Root Sum Squares model is significantly larger than the tolerance allowed by the Worst Case model.

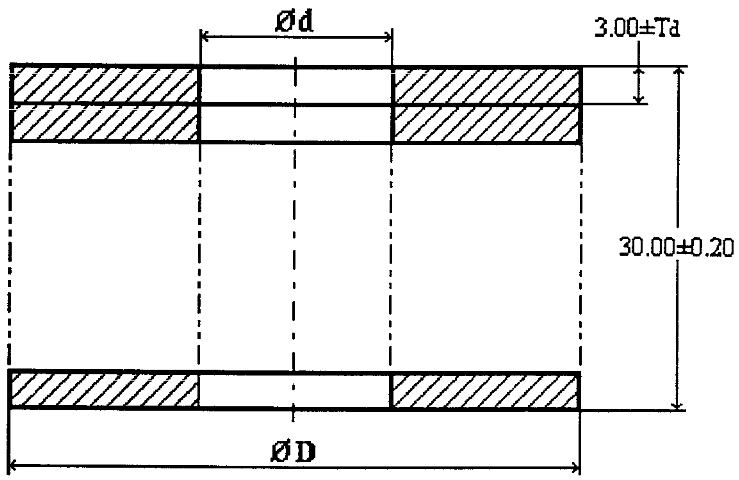



**Figure 2.3 Toleracing of a Stack of Disks**

In real processes the mean of the distribution often shifts away from the nominal dimension due to setup choice or time-varying parameters, such as tool wear. Ignoring the mean shift can be very detrimental, resulting in large errors in estimates of the number of assemblies within specification limits [Spotts, 1978, Evans, 1975]. The example below shows how significantly the mean shift affects the assembly rejection rate.

**Example 2.2:**

Suppose in Example 2.1, the thickness of the disk is distributed as shown in Figure 2.4, with a mean shift of $0.2T_d$. Suppose $T_d$ is still $3\sigma_d$. Keeping the stack height specification the same, the disk thickness has a normal distribution of $d \sim N(3.00+0.2T_d\ ,\ \frac{T_d^2}{9})$ , and the stack height has a normal distribution of

$D \sim N(30.00+10\times0.2T_d\ ,\ \frac{10T_d^2}{9})$ . Substituting $T_d$ = 0.06 mm from Example 1, D∼N(30.12, 0.0632). The accumulated stack height mean shifted 0.12 mm (60% of $T_{assem}$= 0.20mm) from nominal dimension.

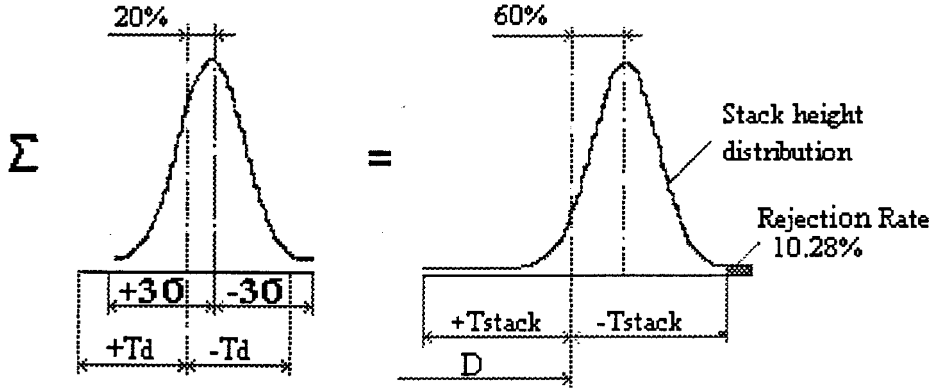



**Figure 2.4 The Effect of Mean Shift on Assembly Dimension**

The upper limit is still 30.00+0.20=30.20 mm, and the rejection rate is

$$1-\Phi(\frac{30.20-30.12}{0.0632}) = 1-\Phi(1.2658) = 0.1028$$

or 10.28%, where $\Phi(Z) = P(x\leq Z)$ (assuming the rejection on the other side of the tail area is negligible). Note that the rejection rate was only 0.27% in Example 1.

In order to take into account the effect of mean shifts and biased distributions, further modifications to the Root Sum Squares model have been proposed by Mansoor [Mansoor, 1963] and Greenwood and Chase [Greenwood and Chase, 1987].

**Mansoor's model:**

$$T_{assem} \leq \Sigma D_i + \sqrt{\Sigma t_i^2} \qquad 2.5$$

**Greenwood and Chase's model:**

$$T_{assem} \leq \Sigma m_i T_i + \left(\frac{Z}{3}\right)\sqrt{\Sigma (1-m_i)^2 T_i^2} \qquad 2.6$$

where $D_i$ is maximum mean shift, $t_i$ is the natural process tolerance and $m_i$ is the mean shift factor for process i. $m_i = \dfrac{mean\ shift}{T_i}$. $m_i$ varies from 0 to 1.

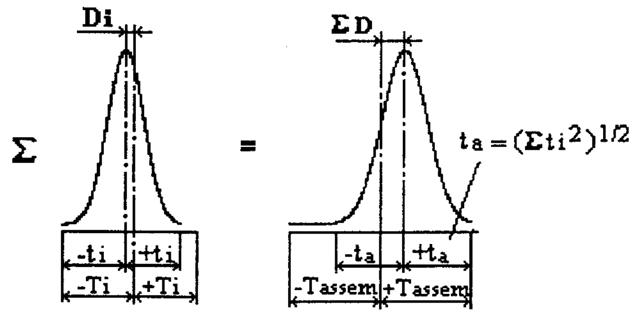



**Figure 2.5 Mansoor's Assumption of Part Dimension Distribution**

Mansoor's model assumes that: (1) tolerance specification is always greater than or equal to the natural process tolerance, i.e., processes are capable of meeting the tolerance specifications; (2) natural process tolerances are normally distributed; and (3) parts are stacked at the maximum mean shift. This model is the sum of the Worst Case and the Root Sum Squares models as shown in Figure 2.5. It is the first model to consider process capability and states that the processes for realizing part dimensional tolerances must be "capable". However, Mansoor's model is conservative as the Worst Case model.

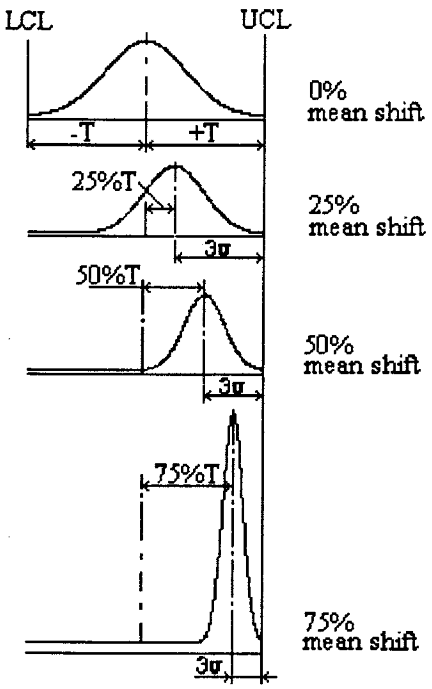



**Figure 2.6 Greenwood and Chase's Assumption of Part Dimension Distribution**

Greeenwood and Chase's model is another attempt to combine the Worst Case and the Root Sum Squares models but it uses an estimated mean shift instead of Mansoor's maximum mean shift. It assumes a 3σ statistical variation in process tolerance from the specification limit. Thus, as the mean shift increases, the standard deviation σ decreases as shown in Figure 2.6. This behavior has little physical meaning. Also, this model does not consider the natural process capability.

**Example 2.3:**

This example compares Mansoor's, and Greenwood and Chase's models. Consider the data given in Table 2.1 on an assembly with six parts.

Table 2.1. Data for Example 2.3

| Component Dimension | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| Tolerance $T_i$ | 3.00 | 1.00 | 0.75 | 0.06 | 0.06 | 0.06 |
| Nature Process Tolerance $t_i$ | 2.25 | 0.60 | 0.45 | 0.04 | 0.04 | 0.04 |
| Maximum mean shift $D_i$ | 0.75 | 0.40 | 0.30 | 0.02 | 0.02 | 0.02 |
| Mean shift factor $f_i$ | 1.5 | 0.25 | 0.25 | 0.75 | 0.75 | 0.75 |

Mansoor's model:

$$T_{assem} = \Sigma D_i + \sqrt{\Sigma t_i^2}$$

$$= (0.75+0.40+0.30+3\times 0.02)+\sqrt{2.25^2+0.60^2+0.45^2+3\times 0.04^2}$$

$$= 3.93 \text{ mm.}$$

Greenwood and Chase's model:

$$T_{assem} = \Sigma m_i T_i + \frac{Z}{3}\sqrt{\Sigma(1-m_i)^2 T_i^2}$$

$$= 0.5\times 3.00+0.25\times(1.00+0.75)+3\times 0.50\times 0.06$$

$$+\sqrt{(0.5\times 3.00)^2+(0.75\times 1.00)^2+3\times(0.50\times 0.06)^2}$$

$$= 3.71 \text{ mm.}$$

Greenwood and Chase's model generally can have smaller assembly tolerance compared with Mansoor's model. But when mean shift is over estimated, then it tends to be a WC model and estimates a more conservative assembly tolerance than Mansoor's model. When the mean shift factor $m_i > 1$, Greenwood and Chase's model no longer has physical meanings and therefore, the part dimension distribution must be within the tolerance specifications.

Another tolerance accumulation model developed by Motorola Corp. is expressed by equation 2.6 [Placek, 1989, Harry et al. 1978].

**Motorola's Model:**

$$T_{assem} \leq Z\sqrt{\Sigma\left(\frac{T_i}{3C_{p,i}(1-m_i)}\right)^2} \qquad 2.7$$

where $m_i = \dfrac{mean\ shift}{T_i}$. Motorola's model is in the form of the Root Sum Squares model but uses an effective standard deviation to account for the process mean shift variations as shown below:

$$\sigma_{e,i} = \frac{T_i}{3C_{p,i}(1-m_i)} \qquad \text{and} \qquad C_{p,i} = \frac{USL-LSL}{6\sigma_{p,i}}$$

where $\sigma_{p,i}$ is the standard deviation of natural process spread, $C_{p,i}$ is the process capability index, $m_i$ is the mean shift factor and $T_i = \dfrac{(USL - LSL)}{2}$. USL and LSL are the upper specification limit and the lower specification limit. This model uses an effective process capability index $\sigma_{e,i}$ to account for the process dispersion which may be caused by uncontrollable random factors and/or inevitable systematic factors like tool wear.

Motorola's model may be used to distinguish between "short term process capability" and "long term process capability" (Figure 2.7). The effective standard deviation $\sigma_{e,i}$ has the same concept of "natural process tolerance" that was used in Mansoor's model. It includes the tolerance specification limits and actual part dimension limits based on process capabilities. Motorola's model is limited by assuming that the part tolerance mean coincides with the midpoint of the specified tolerance. Thus the actual assembly rejection rate can be higher than that yielded by the model.

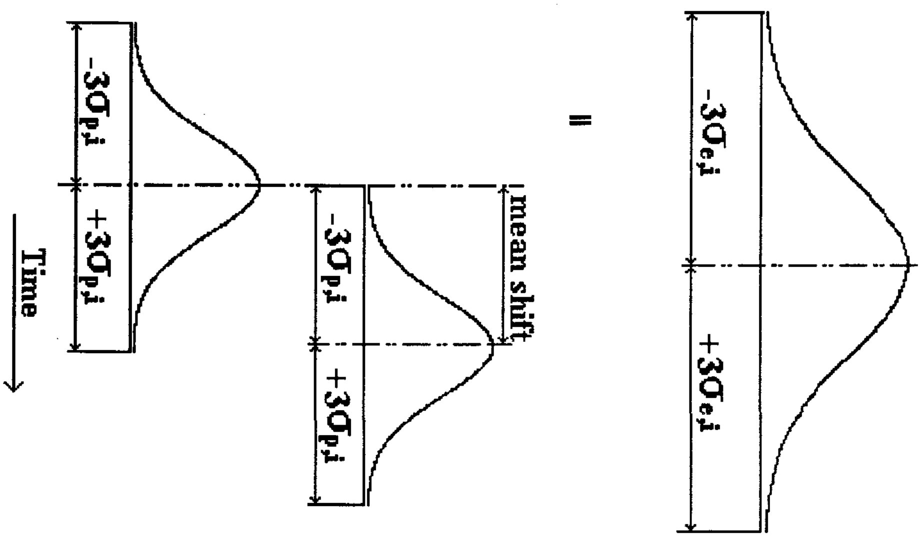



**Figure 2.7 Motorola 6σ Model's Effective Deviation of Process Spread**

## 2.3 Computer Applications of Tolerance Analysis

A primary requirement in concurrent engineering environment is the assignment of manufacturable tolerances to part dimensions and evaluation of tolerances on critical assembly dimensions during the design stage such that potential manufacturing and assembly problems may be reduced. Therefore, it is desired that tolerance design and analysis be performed concurrently with CAD modeling and be able to conveniently (ideally dynamically) update the CAD model based on the results of tolerance analysis. Since the determination of proper tolerances is directly related to the capability of the manufacturing processes to be used, it should also be convenient to access the manufacturing process data.

The above indicated requirements on tolerance analysis have not been fully explored in the development of tolerance design and analysis system from the point of view of design and manufacturing system integration [Soderberg, 1992]. From the CAD perspective, there are many difficulties in representing tolerances on dimensions and geometric features [Juster, 1992]. The capabilities of solid models have to be enhanced to incorporate tolerance along with part geometric and topological information [Roy, 1989, Stewart, 1993]. From the manufacturing process perspective, this is largely due to the fact that most currently available tolerance analysis models do not involve process capability when considering part dimension distributions. There are no real guidelines for the designer to choose proper part dimension tolerances based on manufacturing feasibility [Tipnis, 1988, Chase and Parkinson, 1991]. Lehtihet and Dindelli (1988) have developed a software called TOLCON which integrates Monte Carlo simulation of tolerances with a manufacturing database. It does not involve any CAD system. Soderberg(1992) developed a computer aided tolerance interface between CIMLINC CAD/CAM software and tolerance analysis. This system does not use a database. Dong and Soom(1986) used a CAD database for tolerance analysis of rotational parts.

# Chapter 3 Modified Assembly Tolerance Analysis Model

## 3.1 Stochastic Nature of the Machined Part Dimensions

In order to understand why the tolerance analysis models reviewed in Chapter 2 need modifications, it is necessary to discuss the stochastic nature of part dimensions.

### 3.1.1 The Normality Assumption of Part Dimension Distribution

Part and assembly dimensions such as lengths, widths, thicknesses, hole diameters, distances between hole and pin centers, and distances between faces, and other physical features comprise a class of variables of prime importance in mechanical design. There are many other factors which affect the output of processed dimensions. Production processes that employ cutting tools are subject to change over time. The same is true of rolling and forging processes. Any dimension such as distance between hole centers, distance between two parallel faces, thickness, and length modified by tool wear results in a geometric random process that is nonstationary. If corrections for tool wear are made periodically, the dimensional values restrain the properties of random variables, but the time trend is minimized and it may be possible to consider the random process as approximately ergodic [Haugen, 1980].

Although there are manufacturing processes that produce distributions decidedly non-normal, many are approximately normal. Many process operations naturally generate normal distributions if they are controlled. Conversely, operations where operators work to the high side of tolerances, for instance, result in distributions that are decidedly skewed. Manually operated processes generate distributions different from those obtained from automatic processes. However, if the processes are automated with NC control and statistical quality control is carried out, then the processes can be generally assumed to produce normal distributions.

### 3.1.2 Process Capability and Acceptance Quality Level (AQL)

The capability of a process is evaluated from the output of the process by using the standard deviation. Process capability represents the natural behavior of a process after assignable disturbances are eliminated. It is an inherent phenomenon and is crudely measured by using the estimation of standard deviation from an in-control chart for variation. Since there are many factors which affect the deviation of outputs, the deviations evaluated are certainly dependent on the effort of controlling the assignable factors. However, the capability of a process can be evaluated under specific circumstances and the output of the process is decided by the natural capability [Kane, 1986].

If out-of-tolerance work is to be avoided, the design tolerance specification must exceed the natural process capability. Table 3.1 shows the relationship between the process capability Index ($C_{p,i}$), the expected quality level (AQL), and the number of rejected parts per million (PPM) when the process mean is controlled at midpoint of the tolerance specification range [Montgomery, 1991]. This table suggests that one way to achieve quality levels at a desired rejection rate is to achieve $C_{p,i}$ in excess of a certain value through statistical process control during manufacturing. From the point of view of design, it is the designer's responsibility to assure that the tolerance specifications on part dimensions are based on the capability of the process to be used.

The minimum values of $C_{p,i}$ for various manufacturing situations recommended by Montgomery(1991) are given in Table 3.2.

Table 3.1 The Relationship Between $C_{p,i}$, AQL and PPM [Montgomery, 1991]

| $C_{p,i}$ | AQL(%) | AQL(PPM) |
|---|---|---|
| 0.75 | 2.44 | 24400 |
| 1.00 | 0.26 | 2500 |
| 1.25 | 0.02 | 200 |
| 1.33 | 0.003 | 30 |
| 1.50 | 0.001 | 10 |
| 1.63 | 0.0001 | 1.0 |
| 1.75 | 0.00001 | 0.1 |
| 2.00 | 0.0000002 | 0.002 |

Table 3.2 Recommended Process Capability Indices $C_{p,i}$ [Montgomery, 1991]

| | Two-sided Specification | One-sided Specification |
|---|---|---|
| Existing Process | 1.33 | 1.25 |
| New Process | 1.50 | 1.45 |
| Safety,Strength, or Critical parameter: existing process | 1.50 | 1.45 |
| Safety, strength or critical parameter, new process | 1.67 | 1.60 |

### 3.1.3 Process Mean Shift

It is difficult to assure that a process will generate a normal distribution with a mean equal to the nominal specification value. There are many factors which shift the mean of the process output away from the target value. These factors include:

a) the setup, especially those processes which use forming tools and dies;

b) tool wear in machining or other time-dependent parameters;

c) raw material, for example, each batch of raw material used in machining may differ in mechanical strength, hardness, chemical composition, etc. and affect the output of the process.

Also, it is a common practice in machining to deliberately setup the process target value shifted toward the least material condition to compensate for tool wear, or for economic concerns when parts outside the upper specification limit have different cost penalty than the parts outside the lower specification limit. In general, mean shift may exist whenever $C_{p,i} > 1$.

How much could the mean be allowed to shift is restricted by two dominant factors: process spread and AQL. If the process is under statistical control so that the full process spread ($6\sigma_{p,i}$) is within the tolerance specification limits, the maximum mean shift allowed to occur equals ($T_i$-$t_i$) where $t_i$ is the natural process tolerance ($3\sigma_{p,i}$) and $T_i$ is the specified tolerance. Let m be the mean shift factor,

$$m_i = \frac{\text{mean shift}}{T_i} \qquad \text{and} \qquad \max(m_i) = 1 - \frac{1}{C_{p,i}}$$

Assuming that the process mean is at tolerance specification midpoint, a $6\sigma_{p,i}$ tolerance specification will give an AQL of $2 \times (1-\Phi(3)) = 0.0027$ (Table 3.1). If process mean shifts, the same tolerance specification will not give the same AQL level. However, for a desired AQL level, it is easy to calculate the maximum mean shift allowed if $\sigma_{p,i}$ is known. Alternatively if the mean shift factor is known, the tolerance specification can be determined.

When mean shift exists and all the parts are purposely randomized before assembling, the distribution of part dimensions will feature normal distribution with little mean shift but a larger deviation than process capabilities. If all the parts are drawn from batches or lots directly from the production line without randomizing and each part is processed to the natural process tolerance, the deviations of part dimensions will be near the process capabilities but with considerable mean shift. These factors can be modeled by properly evaluating the process capability index $C_{p,i}$.

### 3.1.4 Process Spread and Tolerance Specification

When $C_{p,i}$ is chosen to be greater than one, the process spread is contained within the tolerance specification but the process mean may not be at the tolerance specification midpoint due to uncontrollable or tolerable factors that cause the process output to shift. Figure 3.1 illustrates the relationship between the tolerance specification and process spread.

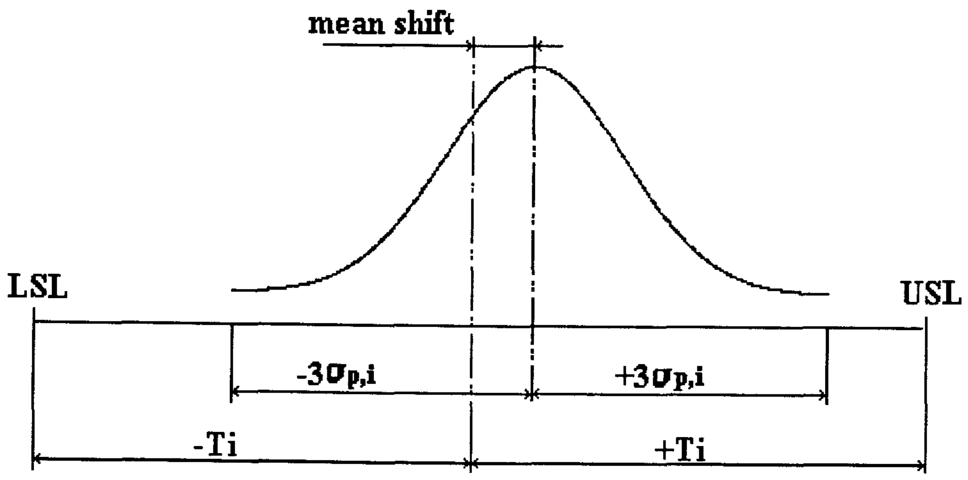



**Figure 3.1 Process Spread and Tolerance Specification**

## 3.2 The Modified Mean Shift Model for Assembly Tolerance Analysis

The proposed mean shift model is based on the following assumptions:

(1) The tolerance specification is always greater than or equal to the natural process tolerance;

(2) Part dimensions produced to the natural process tolerance are normally distributed;

(3) Mean shift generally exists

Figure 3.2 below explains the above assumptions..

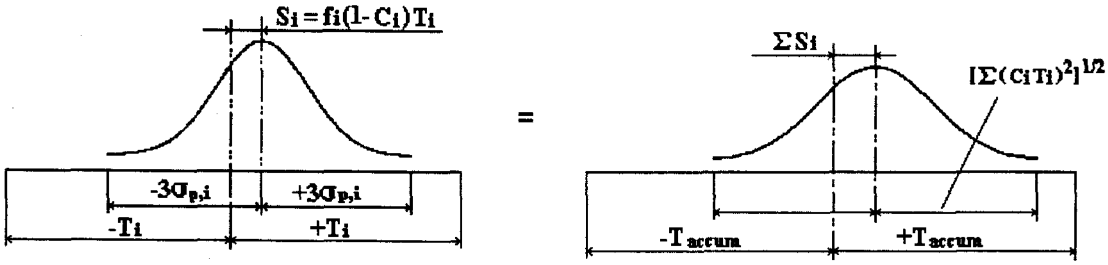



**Figure 3.2 Proposed Mean Shift Model**

Let $f_i$ be the estimated mean shift factor,

$$f_i = \frac{S_i}{T_i - t_i} \qquad 3.1$$

where $S_i$ is the mean shift. When $f_i = 1$, mean shift is at its maximum value $(T_i - t_i)$ within the tolerance specification. When $f_i = 0$, there is no mean shift; when $f_i > 1$, there will be a severe rejection rate in final assembly. Notice here that $f_i$ is defined in proportion to $(T_i-t_i)$ rather than $T_i$, as in Greenwood and Chase's model, and it represents the difficulty experienced in controlling the mean shift rather than simply using the mean shift value.

Let

$$C_i = \frac{1}{C_{p,i}} = \frac{t_i}{T_i} \qquad 3.2$$

where $C_i$ is a factor indicating how much the natural process tolerance covers the tolerance specification. The accumulated tolerance $T_{accum}$ is given as

$$T_{accum} = \Sigma f_i(1-C_i)T_i + (\frac{Z}{3})\sqrt{\Sigma(C_iT_i)^2} \qquad 3.3$$

The accumulated mean and standard deviation is given as

$$\mu_{accum} = \Sigma f_i(1-C_i)T_i \qquad 3.4$$

$$\sigma_{accum} = \frac{1}{3}\sqrt{\Sigma(C_iT_i)^2} \qquad 3.5$$

Therefore

$$T_{accum} = \mu_{accum} + Z\sigma_{accum} \qquad 3.6$$

The AQL for assembly, $AQL_{assem}$ , is given as

$$AQL_{assem} = 1 - \Phi(\frac{T_{assem} - \mu_{accum}}{\sigma_{accum}}) \qquad 3.7$$

where $T_{assem}$ is the specification limit for the assembly dimension and $\Phi$ represents area under the normal curve.

Notice that in equation (3.3), the model gives only the accumulated tolerance, not the assembly tolerance, $T_{assem}$. Since the $AQL_{assem}$ depends on the expected value of accumulated mean $\mu_{accum}$ and standard deviation $\sigma_{accum}$ ; $T_{assem}$ has to be chosen to achieve the required AQL.

In equation (3.3), when $f_i=0$, i.e., when there are no mean shifts, then

$$T_{assem} \leq (\frac{Z}{3})\sqrt{\Sigma(C_iT_i)^2} \qquad 3.8$$

This is a modified Root Sum Squares model, similar to the Motorola's model. When

$f_i = 1$, then a model similar to Mansoor's model results. This condition assumes that parts have the maximum mean shift allowed (depends on the $C_{p,i}$ value chosen) and part tolerances are accumulated as in the Worst Case model, plus the natural process deviations.

The proposed model allows:

(1) assignment of tolerance specifications based on process capabilities. Different values of $C_{p,i}$ and $f_i$ can be selected to account for the degree of uncertainty in individual process characterizations;

(2) flexibility to adjust individual part dimension mean shift within the tolerance specification based on desired assembly AQL in process control.

## 3.3 Application of the Proposed Mean Shift Model

The proposed mean shift model can be widely used in tolerance design and process control in manufacturing. Following are some of the possibilities:

### 3.3.1 Verifying the Desired Assembly AQL when Part Dimension Mean Shift Exists

If a part exhibits mean shift, then a given $C_{p,i}$ will not give the same AQL quality as compared with the case where no mean shift is considered as given in Table 3.2.

Assuming that the part dimension, $d_i$, is normally distributed,

$$d_i \sim N\left( f_i(1-C_i)T_i \, , \, \frac{C_i^2 T_i^2}{9} \right)$$

Then the assembly dimension $D_{assem}$ is also normally distributed,

$$D_{assem} \sim N(\mu_{accum}\ ,\ \sigma^2_{accum})$$

where $\mu_{accum}$ and $\sigma_{accum}$ are given by equations 3.4 and 3.5 respectively , and AQL can be obtained from equation 3.7.

**Example 3.1**

Consider the data given in Table 3.3 consisting of values for $T_i$, $C_i$ and $f_i$ for six parts.

Table 3.3 Data for Example 3.1

| Component Dimension | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| Tolerance $T_i$ | 3.00 | 1.00 | 0.75 | 0.06 | 0.06 | 0.06 |
| Mean shift factor $f_i$ | 0.5 | 0.5 | 0.5 | 0.7 | 0.7 | 0.7 |
| $C_i = 1/C_{p,i}$ | 0.75 | 0.60 | 0.60 | 0.67 | 0.67 | 0.67 |

$$\mu_{accum} = 0.5\times0.25\times3.00+0.5\times0.4\times1.00+0.5\times0.4\times0.75+3\times0.7\times0.33\times0.06$$
$$= 0.7637 \text{ mm.}$$

$$\sigma_{accum} = \frac{1}{3}\sqrt{\begin{array}{l}(0.75\times3.00)^2+(0.6\times1.00)^2\\ \quad +(0.6\times0.75)^2+3\times(0.67\times0.06)^2\end{array}} = 0.7909.$$

$$T_{accum} = \mu_{accum}+3\sigma_{accum} = 3.1397 \text{ mm.}$$

If assembly tolerance specification $T_{assem}$ = 3.50 mm, then

$$AQL_{assem} = 1-\Phi(\frac{3.50-0.7637}{0.7909}) = 1-\Phi(3.4597) = 0.0003$$

or 0.03 %.

Using larger mean shift in the model will yield a more conservative value of $AQL_{assem}$. When maximum mean shift is used, the modified model is identical to Mansoor's model.

### 3.3.2 Adjusting Process Capability $C_{p,i}$ to Accommodate Parts Randomization

An adjusted capability index can be used in this model if the process capability changes due to randomization before assembly. The following example explains this.

**Example 3.2**

Consider the data given in Table 3.3. If certain lot size of part 3 is randomized before assembling, and suppose that the mean shift is reduced to 0.2 from 0.5, the process capability index reduce to 1.2 from 1.67, then

$$\mu_{accum} = 0.5\times0.25\times3.00+0.5\times0.4\times1.00+0.2\times0.17\times0.75 +3\times0.7\times0.33\times0.06$$

$$= 0.6421 \text{ mm.}$$

$$\sigma_{accum} = \frac{1}{3}\sqrt{(0.75\times3.00)^2+(0.6\times1.00)^2+(0.83\times0.75)^2+3\times(0.67\times0.06)^2}$$

$$= 0.8038.$$

$$T_{accum} = \mu_{accum}+3\sigma_{accum} = 3.0535 \text{ mm.}$$

$$AQL_{assem} = 1-\Phi(\frac{3.50-0.6421}{0.8038}) = 1-\Phi(3.5555) = 0.0002$$

or 0.02%.

The above calculations show that the randomization of part 3 reduced the AQL of assembly from 0.03% to 0.02%, improving the assembly quality.

### 3.3.3 Consideration of Dynamic Process Capability

In processes where variation due to a systematic assignable cause exists and is tolerated, such as tool wear, the traditional measure of process capability is invalid as it confounds the true process capability with some measure of assignable cause. Therefore it is necessary to utilize a dynamic model to describe process capability where the capability of the process is considered to be constantly changing as the process ages. $C_{pk}$ [Kane, 1986, Sullivan, 1989] and $C_{pm}$ [Chan et al. 1988, Spiring, 1991, Boyles, 1991] are the two process capability indices which possess the ability to consider process variability when assessing dynamic process capability.

$$C_{pk} = \min\{\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\}$$

where USL and LSL are the tolerance specification limits, $\mu$ is process mean and $\sigma$ is process standard deviation, and

$$C_{pm} = \frac{USL - LSL}{6\sigma'}$$

where

$$\sigma' = E(X - \mu_T)$$

and $\mu_T$ denotes the target value of the process.

The relationship between the dynamic process capability indices $C_{pk}$ and $C_{pm}$ , the traditional process capability index $C_{p,i}$ and the mean shift factor, as derived in Appendix A, can be used in the modified mean shift model. Rewriting the modified mean shift model (Equation 3.3) as

$$T_{accum} = \Sigma\, m_i T_i + (\frac{Z}{3})\sqrt{\Sigma (C_i T_i)^2} \qquad 3.10$$

where $m_i = \frac{S_i}{T_i}$. If $C_{pm}$ is used, process mean shift factor is

$$m_i = \frac{1}{3}\sqrt{\frac{1}{C_{pm,i}^{\ 2}} - \frac{1}{C_{p,i}^{\ 2}}}$$

If $C_{pk}$ is used,

$$m_i = 1 - \frac{C_{pk,i}}{C_{p,i}}$$

The relationship between $f_i$ in equation 3.3 and $m_i$ in equation 3.10 is

$$f_i = \frac{m_i}{1 - \frac{1}{C_{p,i}}} = \frac{m_i}{1 - C_i} \qquad 3.11$$

The following example shows the effect of dynamic mean shift in a part on the AQL of the assembly.

**Example 3.3**

Suppose that in Example 3.1, part 2 is produced by a process which exhibits mean shift character when the process mean target is set at the midpoint of the tolerance specification zone. $C_{p,2}$ is the same as given in Table 3.3, where $C_{p,2} = 1.67$ $\left(C_2 = \frac{1}{C_{p,2}} = \frac{1}{1.67} = 0.6\right)$, and $C_{pk} = \min\{\frac{\mu_T - LSL}{3\sigma}, \frac{USL - \mu_T}{3\sigma}\}$, where $\mu_T$ is process mean. Suppose from previous production, $C_{pk}$ is measured as 1.0, then

$$m_2 = 1 - \frac{C_{pk}}{C_{p,2}} = 1 - \frac{1.0}{1.67} = 0.4012 \text{, recalculating}$$

$$\mu_{accum} = 0.5\times0.25\times3.00 + 0.4012\times1.00 + 0.5\times0.4\times0.75 + 3\times0.7\times0.33\times0.06$$
$$= 0.9678.$$

$$AQL_{assem} = 1 - \Phi\left(\frac{3.50 - 0.9678}{0.7909}\right) = 1 - \Phi(3.2017) = 0.0007 \quad \text{or } 0.07\%.$$

The above calculated AQL is higher compared with the AQL calculated in Example 3.1 without dynamic mean shift, indicating that the assembly rejection rate will be higher when dynamic mean shift is taken into account.

### 3.3.4 Providing Guidance for Tolerance Allocation and Process Control

Given the desired AQL level and the assembly tolerance specification, the mean shift model gives a guidance on where the part tolerances should be tightened and how it will affect the assembly tolerances.

At the production stage when the assembly AQL is given, the goal of manufacturing would be to achieve the desired AQL with the least expense. The modified mean shift model can give guidance on which part quality has to be improved and how the improvement in quality can be achieved, so that the desired assembly AQL could be realized.

# Chapter 4 Development of An Assembly Tolerance Analysis System

Due to the complexity of tolerance analysis problem and the various types of data needed to perform tolerance analysis, a computer system that assists the user perform tolerance analysis and design is greatly needed. Such a system must be integrated with CAD modeling and process database. This chapter describes the framework and implementation of such a system.

## 4.1 Strategy of System Development

From the aspect of design, tolerance analysis is used to assure good manufacturability of each part dimension and to assure that the manufactured parts can be assembled into a product. From the aspect of manufacturing, tolerance analysis is used to control the production quality by assuring the capabilities of processes and controlling the mean shifts of the processes so that manufactured parts will assemble at the assembly line. Therefore, the tolerance analysis program must be integrated with CAD and process database. Actual design refining process may involve many aspects of measurements, but tolerance is an important one especially when one is concerned with manufacturing yield, product defects due to manufacturing quality, and production cost.

A key point in integrating a tolerance analysis model to CAD and other programs is sharing data between different programs. Under the traditional single task operating system (DOS) in microcomputers, sharing data requires that the program modules be put under the same overhead in a single task or via file transforming. The former requires tolerance program be part of the same program as CAD or process control program; the later poses great deal of difficulty for dynamic access of data and slows down the overall speed. There are many programs developed to solve almost any specific engineering problem. However, these programs are mostly designed to run under a single overhead and only one program can be executed at a time. The limitation of these programs lies in the fact that there are too many aspects involved in a real design problem. The solution would require involving several computer applications and different types of data. The program inevitably becomes too large and fairly complex [Turner,1991, Suvajit, 1991 and Stephen, 1990]. This causes difficulty for the end user to learn to use it. There is a need to be able to use these applications integrally.

Due to developments in hardware and operating system like Microsoft Windows 3.1 and IBM OS/2.x, the power of PCs has increased dramatically during last several years. Windows 3.1 and OS/2.x are of multitasking nature and therefore allow the possibility for integration of different software packages of different functionalities and sharing of data between different programs. This concept has indeed become the main stream of PC software development [Miller, 1993,1994]. Instead of including all the application modules for performing different tasks involved in solving a complex engineering problem in a large scale software package, the programs can be run concurrently sharing data in between as needed through Dynamic Data Exchange (DDE) or Object Linking and Embedding (OLE). This system is able to run a much larger number of applications concurrently and integrally which then forms a more sophisticated design environment as needed. Under Windows 3.1, the application support DDE can establish links between several applications and exchange data or pass remote commands dynamically or as required. With OLE, one or more server applications can be linked to or be embedded in a specific document of a client application. The user can access a server application from the client application in which the server application data are linked or embedded. Both DDE and OLE have become industry standards in computer software development.

The tolerance analysis system described here is chosen to be implemented as a single program running under Windows to perform tolerance analysis and other necessary functions, and integrated with CAD and a manufacturing database through DDE and OLE. The program is designed with the understanding that it can later be integrated into a lager scale product development system via a similar mechanism. Therefore, each module is designed as generically independent as possible.

## 4.2 System Description

The tolerance analysis system consists of four major components as shown in Figure 4.1.

1) CAD package: a parametric 2D CAD modelling package DesignView 3.0 was chosen because it supports dynamic data exchange (DDE) and was available at the time this research started. However, other CAD programs designed for Windows featuring DDE and OLE support are equally supported, such as AutoCAD 12 for Windows.

2) Tolerance analysis program: This program makes several tolerance analysis models available to the user. These models include the Worst Case, the Root Sum Squares, the Six Sigma and the Mean Shift models as described in Chapter 3. The program also features:

. A graphical presentation of tolerance chain to assist users visualize the relationship between different parts in the assembly and ease the input of both dimension and tolerance values.

. Guidelines to select fit classes and tolerance limits of different fit classes according to the American-British-Canada Agreements (ABC) as listed in Tool Design, Second Edition (Pallack, 1988).

. Direct access to a manufacturing process database for the user to select proper processes capable of meeting the required precision.

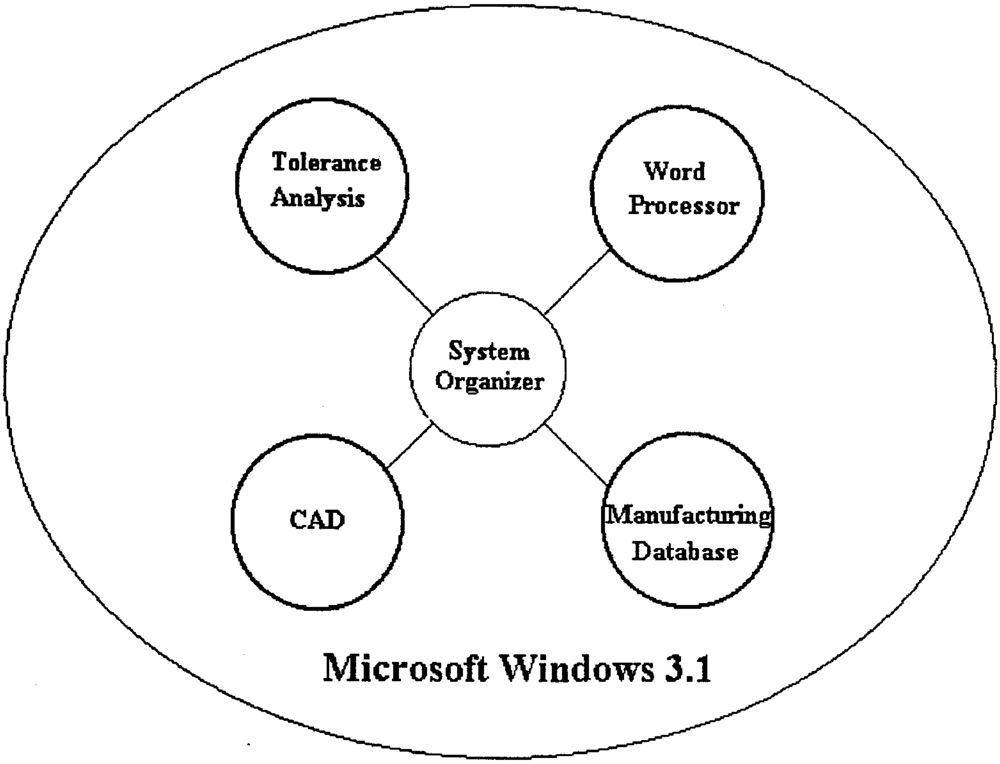



**Figure 4.1 System Components**

. Dynamic data exchange with the CAD program. The user can get data from the CAD drawing and update the CAD drawing from inside the tolerance analysis program.

. OLE client support: If the CAD program supports OLE, then the CAD drawing can be linked or embedded into the tolerance analysis program.

. Full graphical user interface. The program has a full menu driven command system as well as graphical command icons or buttons. At low level, all commands can also be performed from the keyboard.

3) Manufacturing database: The manufacturing database contains natural process tolerance and process capability information for various machining processes available in the factory. This database captures the knowledge of manufacturing engineers about existing processes. In order to allocate tolerance to a part dimension the user selects an appropriate machining process and retrieves relevant process data. In this system, a database covering several conventional machining processes is built using Microsoft Access 1.1 database engine. All the data collected are derived from Pollack's Tool Design (1988) book as shown in Table 4.1. As it is not the main objective of this research to develop a manufacturing process capability database, and data collection on the capabilities of different processes requires resources that are not currently available for this research effort, the database presented here is merely used for the purpose of explaining the mechanism of system integration and the use of the proposed tolerance analysis model.

4). An integrated report writing tool. The user can choose any of the word processing tools available under Windows system and access it from inside the tolerance analysis program. The user can copy and paste data from tolerance analysis program to a word processor via Windows clipboard.

**Table 4.1 Expected Precision of Machining Processes [Pollack, 1988]**

| Norminal Size Range (in.) over - to | Grade | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| | Tolerance (thousandths) | | | | | | | | | |
| 0.04-0.12 | 0.15 | 0.20 | 0.25 | 0.40 | 0.60 | 1.00 | 1.6 | 2.5 | 4.0 | 6.0 |
| 0.12-0.24 | 0.15 | 0.20 | 0.30 | 0.50 | 0.70 | 1.20 | 1.8 | 3.0 | 5.0 | 7.0 |
| 0.24-0.40 | 0.15 | 0.25 | 0.40 | 0.60 | 0.90 | 1.40 | 2.2 | 3.5 | 6.0 | 9.0 |
| 0.40-0.71 | 0.20 | 0.30 | 0.40 | 0.70 | 1.00 | 1.60 | 2.8 | 4.0 | 7.0 | 10.0 |
| 0.71-1.19 | 0.25 | 0.40 | 0.50 | 0.80 | 1.20 | 2.00 | 3.5 | 5.0 | 8.0 | 12.0 |
| 1.19-1.97 | 0.30 | 0.40 | 0.60 | 1.00 | 1.60 | 2.50 | 4.0 | 6.0 | 10.0 | 16.0 |
| 1.97-3.15 | 0.30 | 0.50 | 0.70 | 1.20 | 1.80 | 3.00 | 4.5 | 7.0 | 12.0 | 18.0 |
| 3.15-4.73 | 0.40 | 0.60 | 0.90 | 1.40 | 2.20 | 3.50 | 5.0 | 9.0 | 14.0 | 22.0 |
| 4.73-7.09 | 0.50 | 0.70 | 1.00 | 1.60 | 2.50 | 4.00 | 6.0 | 10.0 | 16.0 | 25.0 |
| 7.09-9.85 | 0.60 | 0.80 | 1.20 | 1.80 | 2.80 | 4.50 | 7.0 | 12.0 | 18.0 | 28.0 |
| 9.85-12.41 | 0.60 | 0.90 | 1.20 | 2.00 | 3.00 | 5.00 | 8.0 | 12.0 | 20.0 | 30.0 |
| 12.41-15.75 | 0.70 | 1.00 | 1.40 | 2.20 | 3.50 | 6.00 | 9.0 | 14.0 | 22.0 | 35.0 |
| 15.75-19.69 | 0.80 | 1.00 | 1.60 | 2.50 | 4.00 | 6.00 | 10.0 | 16.0 | 25.0 | 40.0 |
| Machining Operation | | | | | | | | | | |
| Lapping-honing | — | — | | | | | | | | |
| Cyl. grinding | | — | — | — | | | | | | |
| Surface grind | | — | — | — | — | | | | | |
| Diamond turining | | — | — | — | | | | | | |
| Diamond boring | | — | — | — | | | | | | |
| Broaching | | | — | — | — | | | | | |
| Reaming | | | | — | — | — | — | | | |
| Turning | | | | | — | — | — | — | — | — |
| Boring | | | | | — | — | — | — | — | — |
| Milling | | | | | | — | — | — | — | — |
| Shaping-planing | | | | | | | — | — | — | — |
| Drilling | | | | | | | — | — | — | — |

## 4.3 Structure of Tolerance Analysis Program

The tolerance analysis computer program, named ToleNet, is developed using Microsoft Visual Basic 3.0. It includes seven main functional forms, one code module and three other form modules. A form module is either referred as a "form" or as a "window" depending upon the way it is used. The structure of the program is shown in Figure 4.2. The detailed menu structures of each form are shown in Figure 4.3.

More information about the program can be found in Appendix B: ToleNet User's Guide.

## 4.4 Integration of Tolerance Analysis System with CAD and Manufacturing Process Database

The four elements of the system described above are integrated as shown in Figure 4.4.

In the system shown in Figure 4.4, The data flow between CAD drawing and tolerance analysis module are realized through DDE. The tolerance analysis module can also be used as the interface to CAD program via OLE, if the CAD package can be used as an OLE server. The link between tolerance analysis module and manufacturing database is realized through the data accessing controls of Visual Basic 3.0. The link between tolerance analysis module and word processor is via Windows Clipboard, while the link between CAD drawing and word processor can be realized using either Clipboard or OLE.

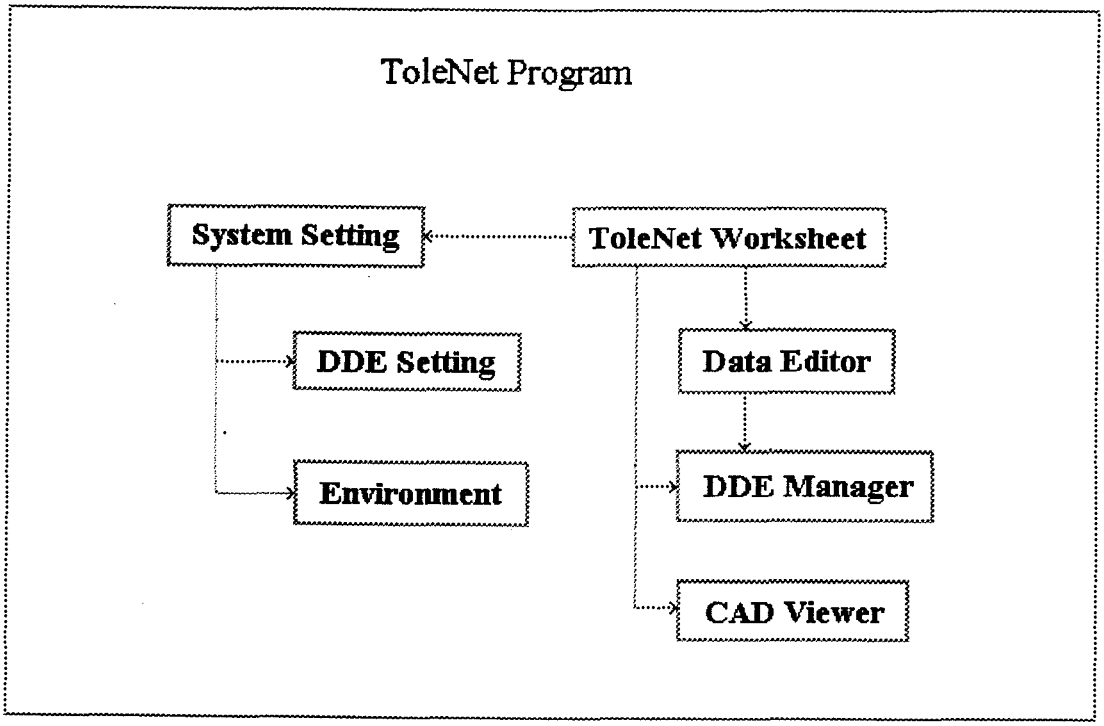



**Figure 4.2 Tolerance Analysis Program Structure**

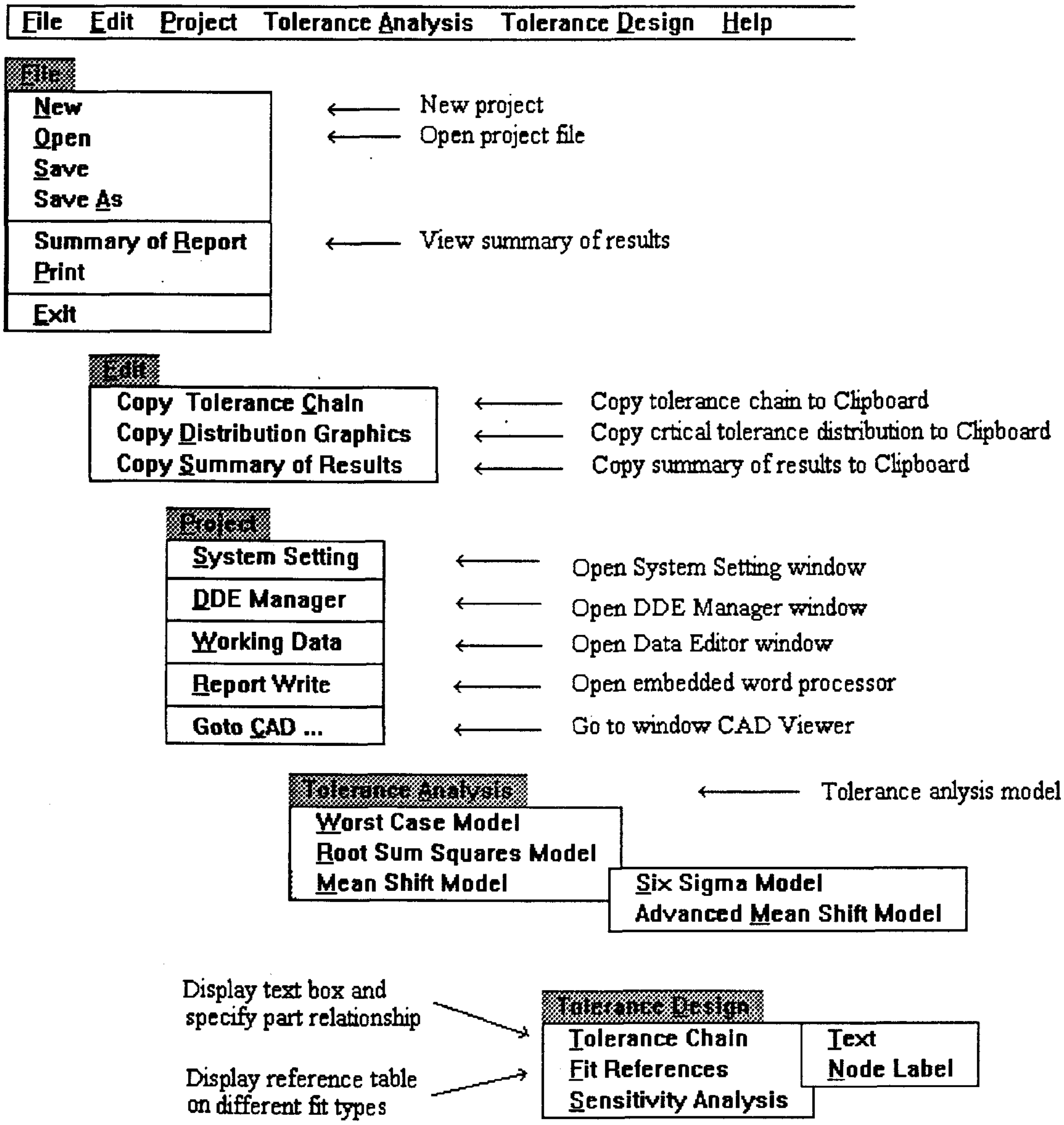



**Figure 4.3 ToleNet Program Menu**

**Figure 4.3.a ToleNet Worksheet Menu**

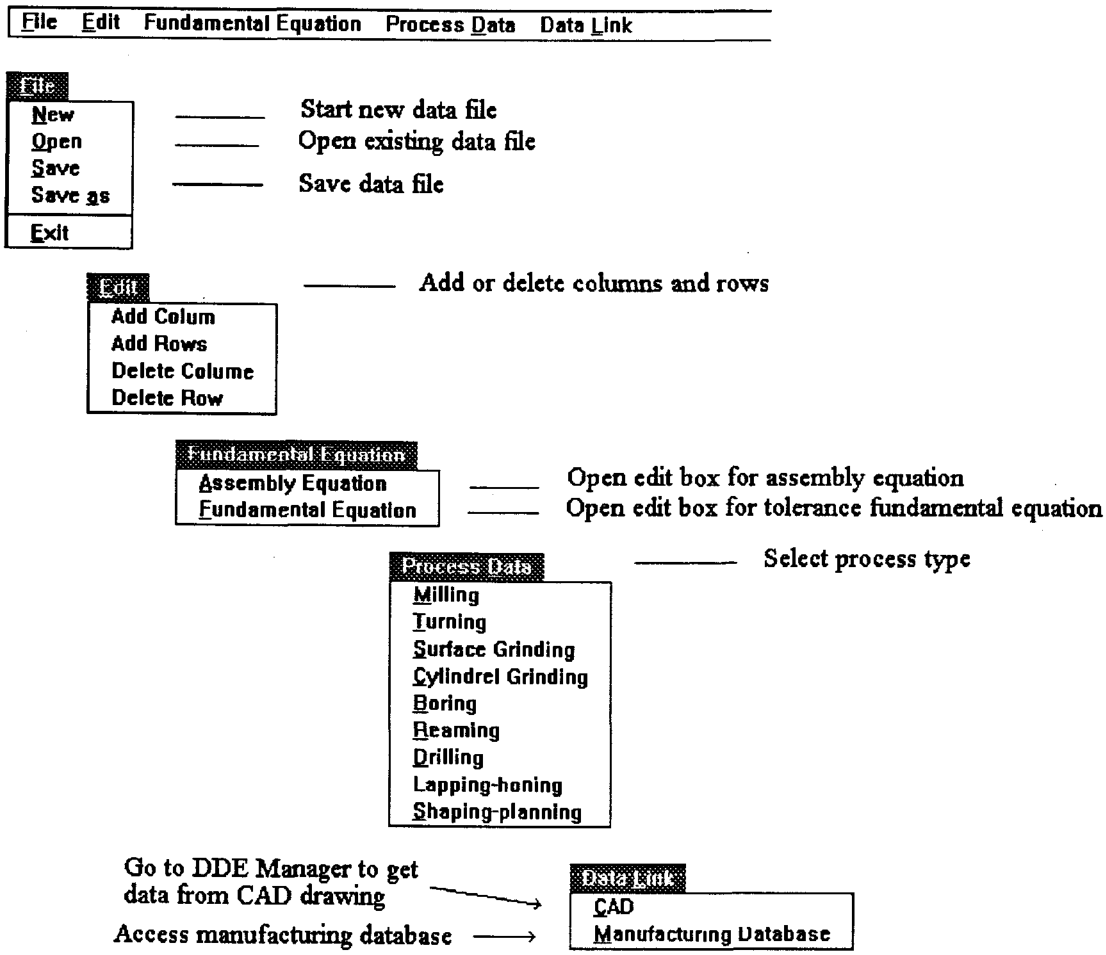



**Figure 4.3.b Data Editor Menu**

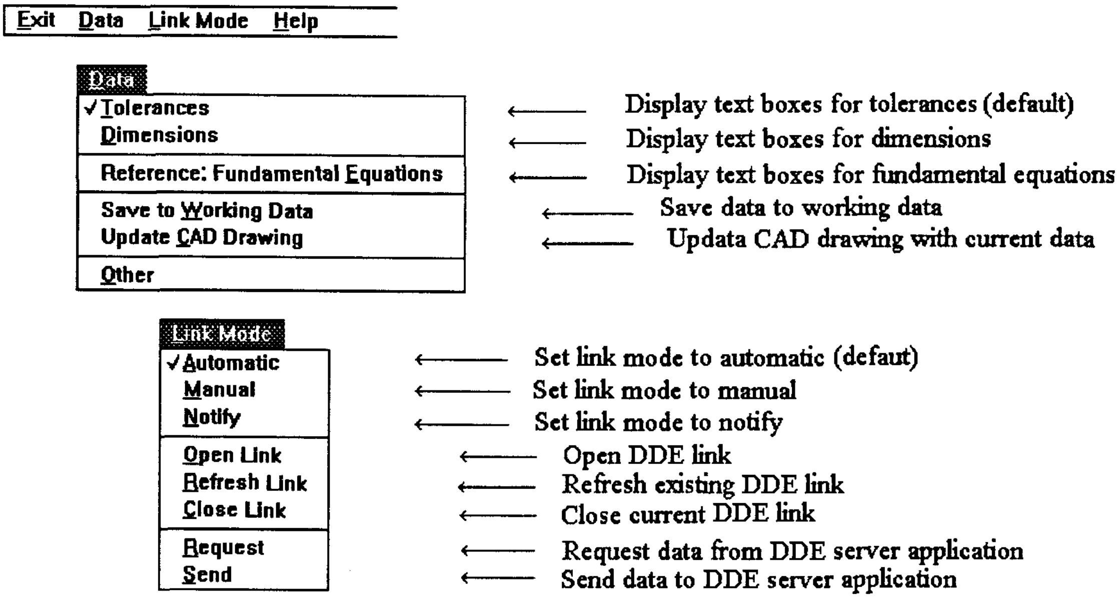
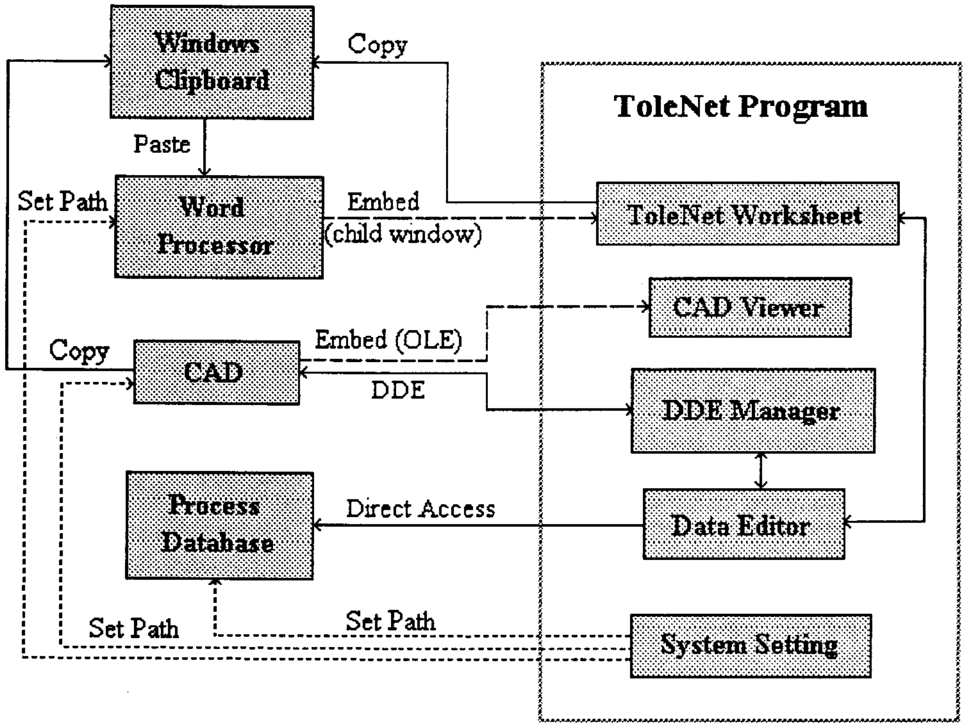



**Figure 4.3.c DDE Manager Menu**




**Legend:**

| | |
|---|---|
| -------------- | system integration path setting |
| — — — — — | integration method |
| ———— | Data link(flow) |

**Figure 4.4 System Integration**

**DDE operation:**

DDE between CAD drawing and tolerance analysis program is managed by the DDE Manger. From inside DDE Manager, user can link data between ToleNet to CAD program or any other DDE supporting program. The DDE Manager is generically independent of the rest of the programs in terms of functionality. It only provides the data link to module Data Editor. Therefore it is a common tool to any form module in the program. This allows the possibility of including additional form modules in the future expansion of the system.

To be used in connection with ToleNet, the CAD program must support Dynamic Data Exchange (DDE). Also, the CAD program must support external accessing of geometric entity dimensions and tolerances.

**OLE operation:**

ToleNet includes a generically independent form module called CAD Viewer to link or embed an OLE object from the CAD program. By linking or embedding an OLE object, tolerance analysis program can act as a front interface of the CAD program to which the OLE object belongs. The CAD drawing can be linked to the CAD Viewer form and the user can access the CAD drawing by accessing the form. The CAD program will then start with the embedded drawing loaded for the user designing or editing. After the user has finished working with the CAD drawing, the CAD program is exited. The embedded object inside the form will then show the change user has made.

## 4.5 System Operation

The following steps are performed in order to use the system:

1). Define the system

The user defines the CAD program and the manufacturing database to be integrated with the tolerance analysis program by specifying the path, name and start command of each application on the window System Setting.

2). Design the assembly or part in CAD program (geometric modelling)

The user designs assembly (assembly drawing) and parts (part drawing) in the CAD program, labelling each dimension and tolerance value needed in the tolerance analysis process as separate variables.

3). Edit working data

The user designs or edits working data necessary for tolerance analysis in the window Data Editor. The original data about dimensions and tolerance specifications can be imported into the program from inside the window DDE Manager. To help specify the necessary parameters about process capabilities, the user can access specified manufacturing database from inside the window Data Editor, use the text boxes which are capable to link to and browse through the specified database tables. The edited data can be saved into a data file and be retrieved into the program. The window Data Editor serves as a common data platform for the entire tolerance analysis program.

4). Tolerance analysis or design

The tolerance analysis program will generate a tolerance chain for the assembly according to the data imported from the CAD or the data the user designed in the window Data Editor. Then the user can choose a tolerance analysis model to perform tolerance analysis. According to the results of tolerance analysis the user can adjust the tolerance values in the Data Editor or the text boxes provided with the tolerance chain in the window ToleNet Worksheet and perform tolerance analysis again until a satisfactory result is obtained. User can also specify the parts mating relations shown on the tolerance chain node. A help guideline is provided when user clicks on the Help label.

4). Report witting

A user selected word processor can be integrated in the program by setting it to be a child window of the window ToleNet Worksheet, or the user can start word processing program separately. The user can copy the results data from ToleNet Worksheet into Windows clipboard and then paste it into the report. This gives the user the full power of the word processor.

5). Updating the CAD drawing

The resulting tolerance value can be exported to the CAD drawing through DDE to update the tolerance values in the CAD drawing. This can be conveniently done from inside the window DDE Manager.

As an alternative, the user can set DDE link from inside the CAD drawing to the ToleNet window DDE Manager so that any changes made in the tolerance analysis program will dynamically update the tolerance value in the CAD drawing. All the DDE links in the CAD drawing can be saved as part of the drawing file. Each time the drawing file is opened, the system prompts the user to update the link.

# Chapter 5 Using the Developed System

In this chapter, an application is presented in detail to explain how to use ToleNet integratively with CAD modelling program DesignView 3.0 and a manufacturing process database.

## 5.1 A Gear Box Example

The assembly model shown in Figure 5.1 is a gearbox axial assembly. The model is developed in DesignView 3.0 and is saved as file GEARBOX.DV. In the drawing, part dimensions and tolerances are labeled as Xi and Ti (i = 1-5) respectively, the assembly

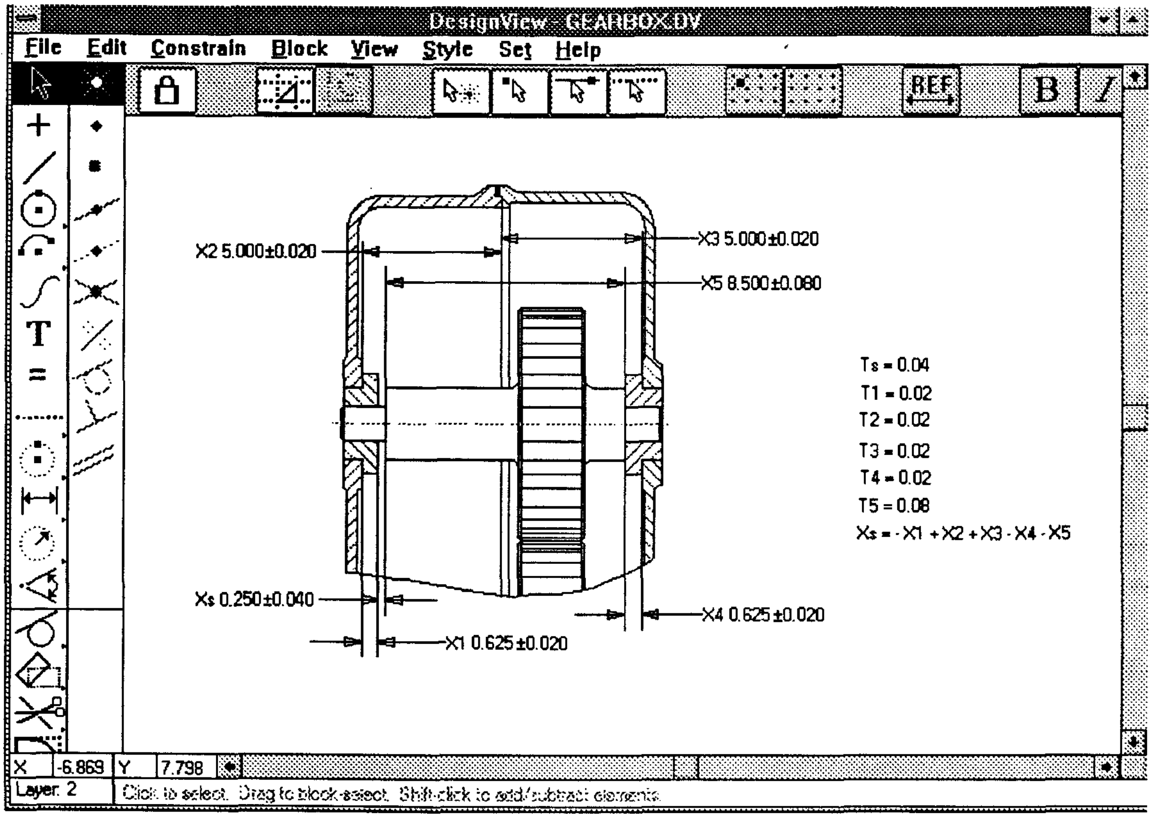



**Figure 5.1 GEARBOX.DV Drawing**

sum dimension and its tolerance are labeled as Xs and Ts respectively. The user specifies the fundamental equation for the assembly sum dimension on the drawing (file GEARBOX.DV is included in the attached program disk). In this example, the assembly critical sum dimension is the clearance between the end of the shaft shoulder and the end of the left bearing. This clearance controls the free play of the shaft along the axial direction. The design specification on this clearance is 0.250±0.040". If the Worst Case or Root Sum Squares model is employed, the assigned part tolerances will not meet the design specification on the clearance. The objective of the project is to adjust part tolerances (as large as possible) to meet the clearance specification .

## 5.2 Setting the Integrated Tolerance Analysis System

To start this project, from the window ToleNet Worksheet, the window System Setting

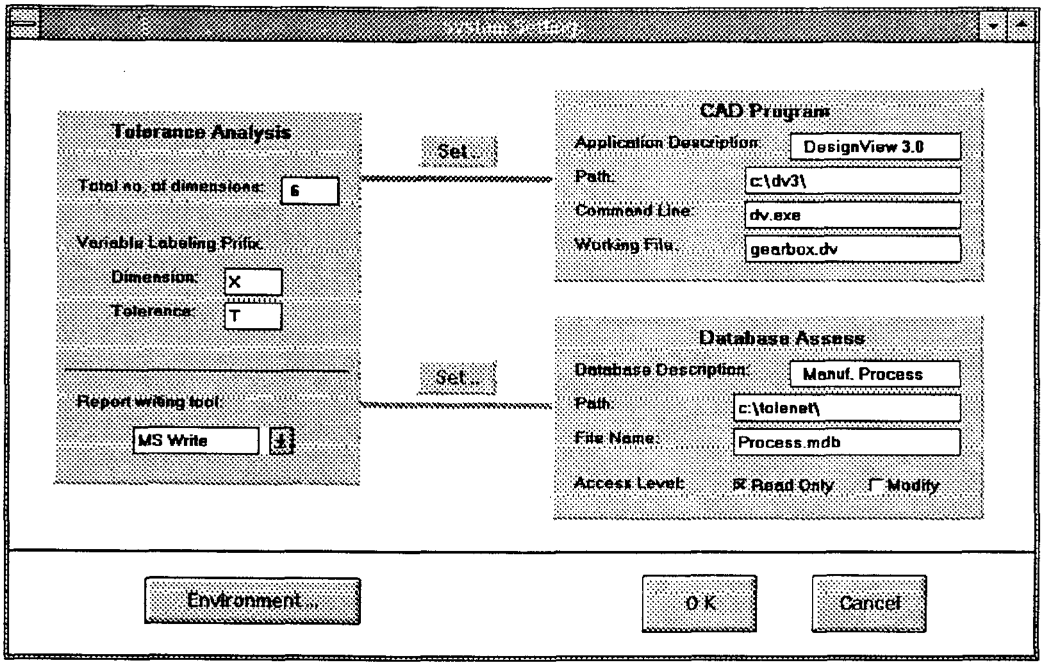



**Figure 5.2 System Setting**

is opened to set the system as shown in Figure 5.2. Additional settings about the DDE and Environment variable are accessed through the command buttons Set... and Environment.

## 5.3 Retrieving Data from CAD Drawing via DDE

The System Setting is closed and DDE Manager is opened. From DDE Manager, user can choose Open Link form menu Link or click on command button Open Link. The dimensions and tolerances labels are displayed in the left column of text boxes, and the values of the dimensions and tolerances are displayed in the right column of text boxes as shown in Figure 5.3. When performing the DDE operation, if DesignView is not open, the program will prompt the user to open it first and load the specified drawing file. The data on dimensions and tolerances is saved into a local working database by selecting Save to Working Data or Close options.

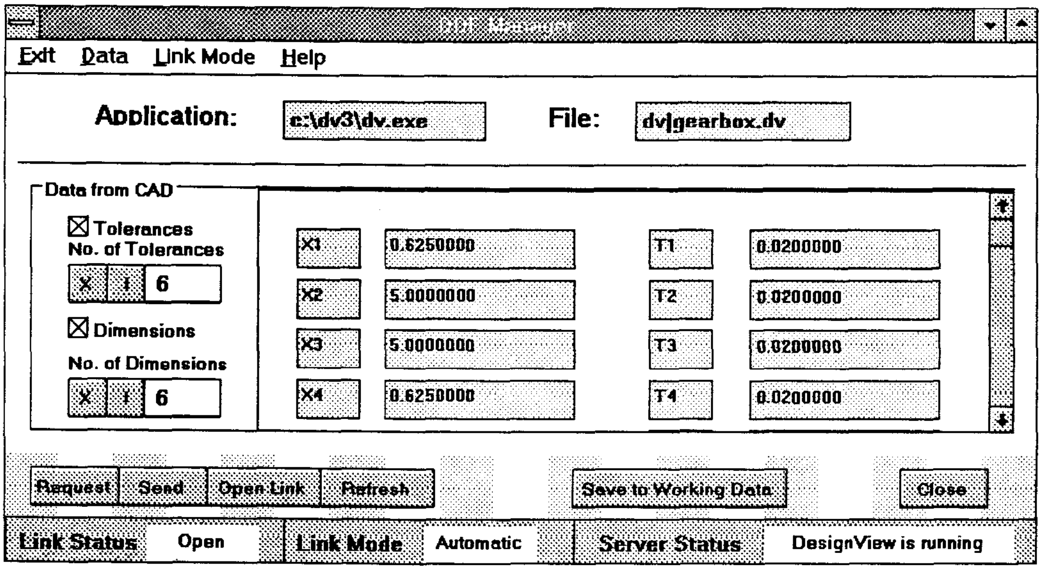



**Figure 5.3 DDE Manager**

## 5.4 Selecting a Tolerance Analysis Model and Preparing the Data

Assume this product is a standard product and is produced in large quantities. Also assume that the machining process is automated and the processes are under statistical quality control. Therefore, the mean shift model described in Chapter 3 can be suitably used for tolerance analysis.

To edit the working data for tolerance analysis, the window Data Editor is opened. The user can enter and edit data much like in a regular spread sheet program. For each dimension and tolerance, the user can choose an appropriate machining process and retrieve data on the natural process tolerance, the mean shift, and the process ID number from the lower portion of the window. If the user chooses not to access the manufacturing database, the lower portion of the widow showing the database records will not be displayed. An edited data set for this example is shown in Figure 5.4.

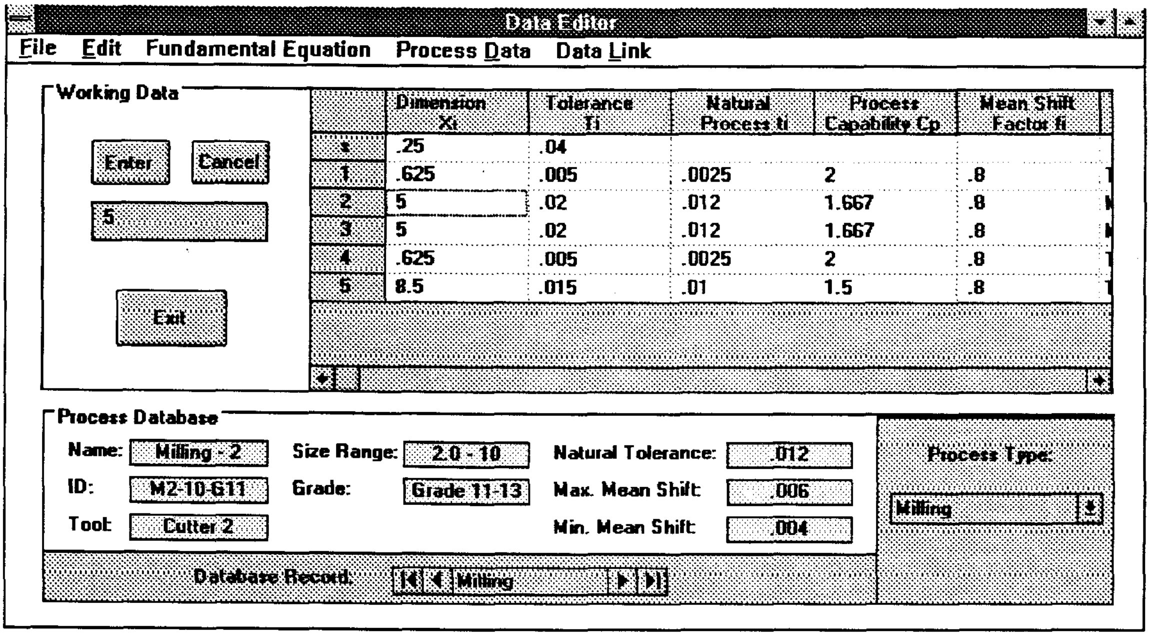



**Figure 5.4 Data Editor**

Returning back to the window ToleNet Worksheet, a tolerance chain is generated in the upper left portion of the window while all the working data including the sum (critical) dimension are displayed in the upper right portion of the window, as shown in Figure 5.5.

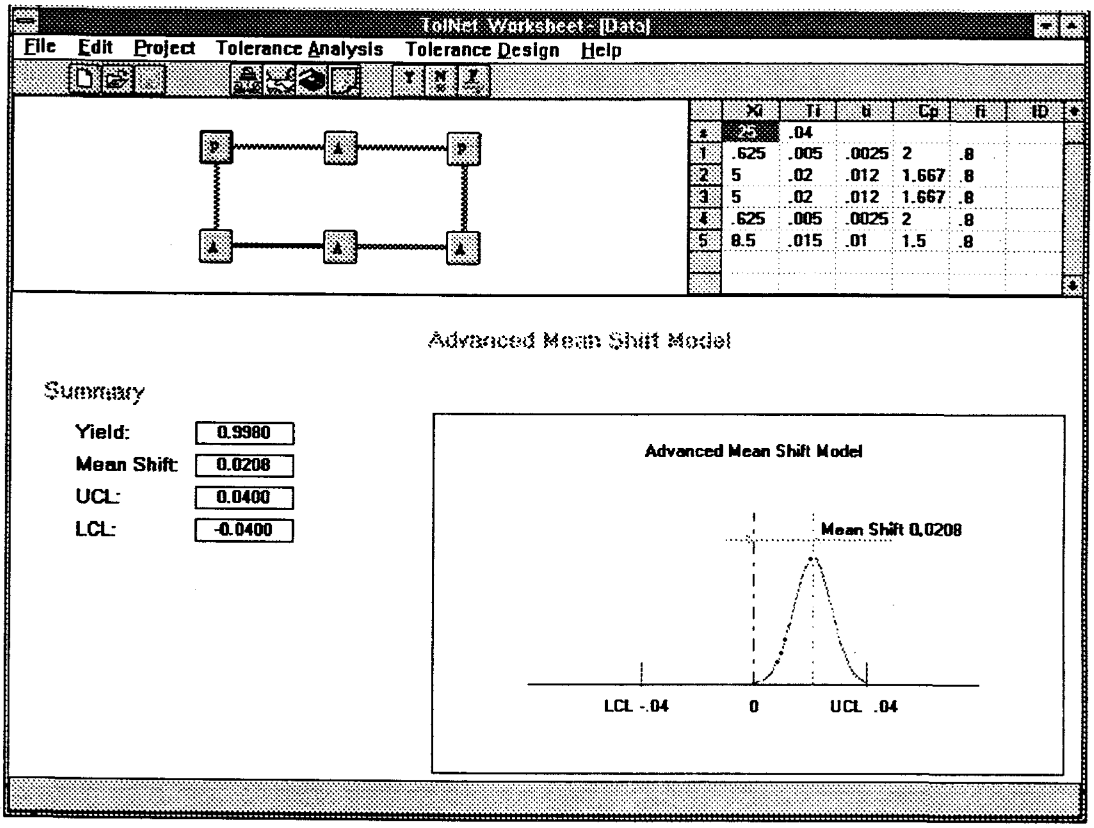



Figure 5.5 ToleNet Worksheet

After the tolerance chain is generated, the user can edit dimensions and tolerances in the text boxes shown on the tolerance chain. Select Text from the menu Tolerance Design to display the text boxes corresponding to each dimension. If Fit Reference from menu Tolerance Design is selected, a table containing several commonly used fit types, size ranges and tolerance values will be displayed on the right portion of the window ToleNet Worksheet. Figure 5.6 shows the tools for assisting in the tolerance design described above.

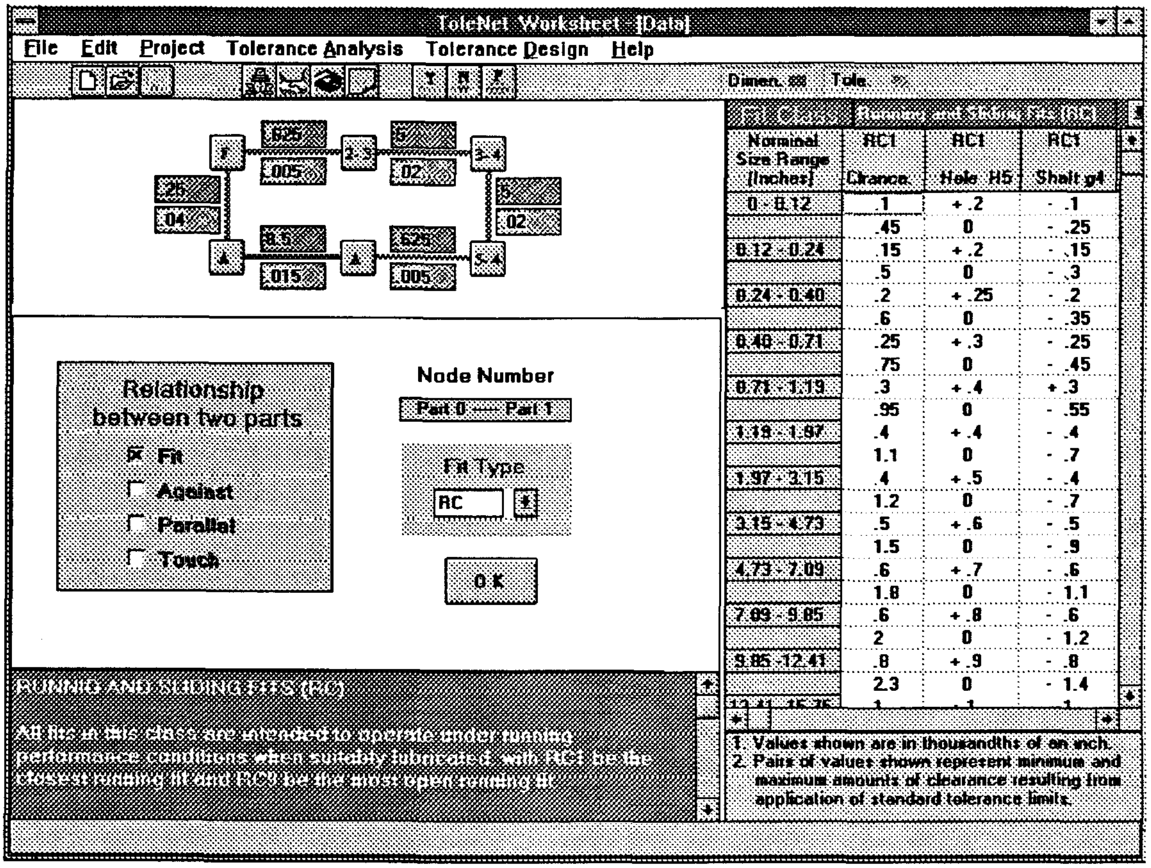



**Figure 5.6 Tools for Assisting Tolerance Design Process**

The user can also specify the mating relationship between adjacent parts. These relationships are classified as against, parallel and fit, as shown in Figure 5.7. The user can click on the tolerance chain node to display a window for specifying these relationships as shown in Figure 5.6. The bottom panel of this window displays the information about the relationship type.

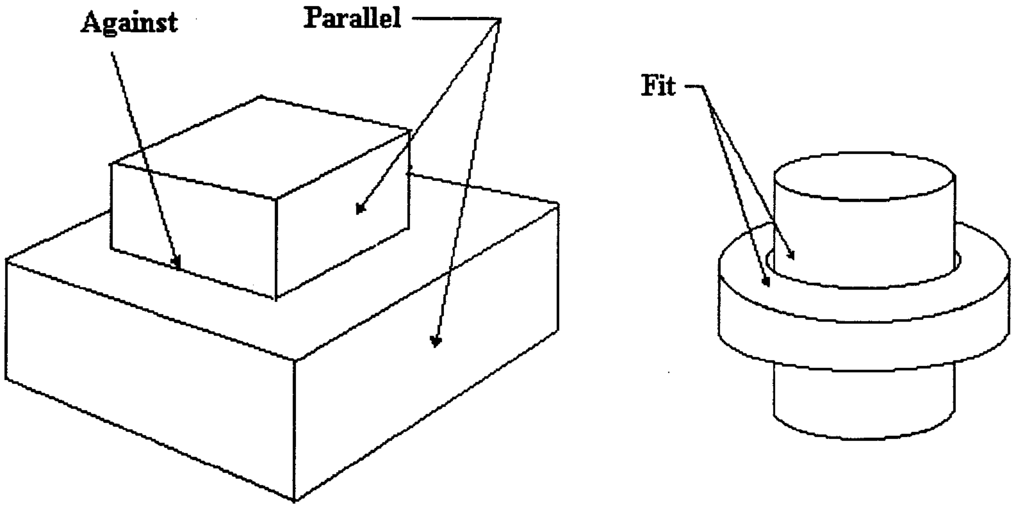



Figure 5.7 Parts Mating Relationships

## 5.5 Performing Tolerance Analysis

To perform tolerance analysis, tolerance analysis model is selected from the menu Tolerance Analysis. For this example, the Advanced Mean Shift Model is selected. The results of tolerance analysis are shown on the lower portion of the window, as shown in Figure 5.5. On the left of the lower portion of Figure 5.5 are the summary of results of the assembly clearance Xs distribution parameters and specification limits. On the right portion of Figure 5.5 is the graphical display of distribution of assembly clearance tolerance Ts. The yield rate for acceptable assembly clearance is 99.80%. The mean shift of the assembly clearance Xs is 0.0208 when the part dimension tolerances are specified as the value given in the second column in the upper right datagrid and the clearance specification is at $\pm 0.04$.

The results can be saved by selecting Save from the menu File.

## 5.6 Updating the CAD Drawing

To update the CAD drawing, return back to the DesignView drawing and make following changes in equations as shown below*:

$$Ti = TiP \qquad (i = 1 - 5, s)$$

here "P" is a suffix added to the variable Ti for substitution of Ti for use in the DDE operation. It is specified in System Setting window and it can be any character the user may choose. Then the user open the window DDE Manager and choose Update CAD Drawing. The data will be copied back to the CAD drawing as shown in Figure 5.8.

## 5.7 Writing Output Report of Results

To write output report, the user selects Report Writing from the menu Project. An user selected word processor from System Setting will be opened. The user can copy the results of the tolerance analysis to Windows clipboard and then pasted into the word processor, as shown in Figure 5.9.

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* This is due to the limitation of DesignView to perform DDE operations. In general, a well behaved DDE support program does not require a remote application to send DDE messages to a separate variable when using DDE "poke" command. For detailed information, please see DesignView 3.0's "reademe.txt" file.

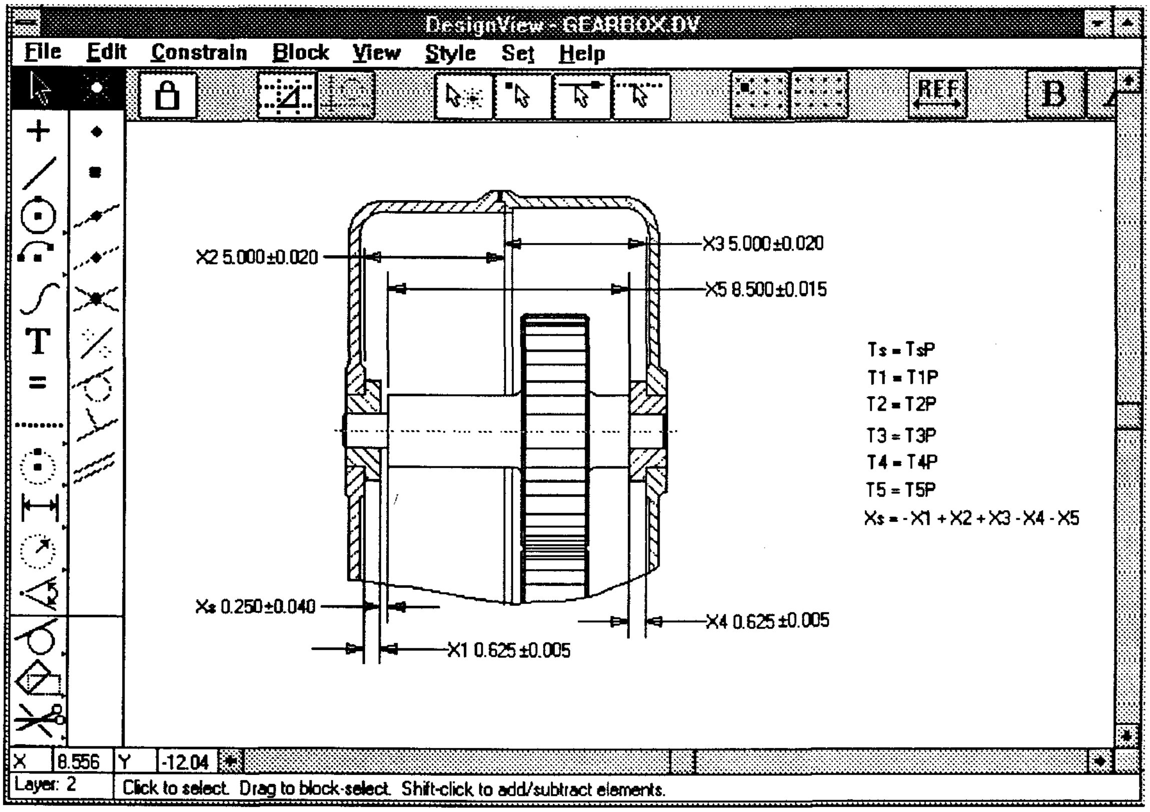


**Figure 5.8 GEARBOX.DV Drawing Updated**

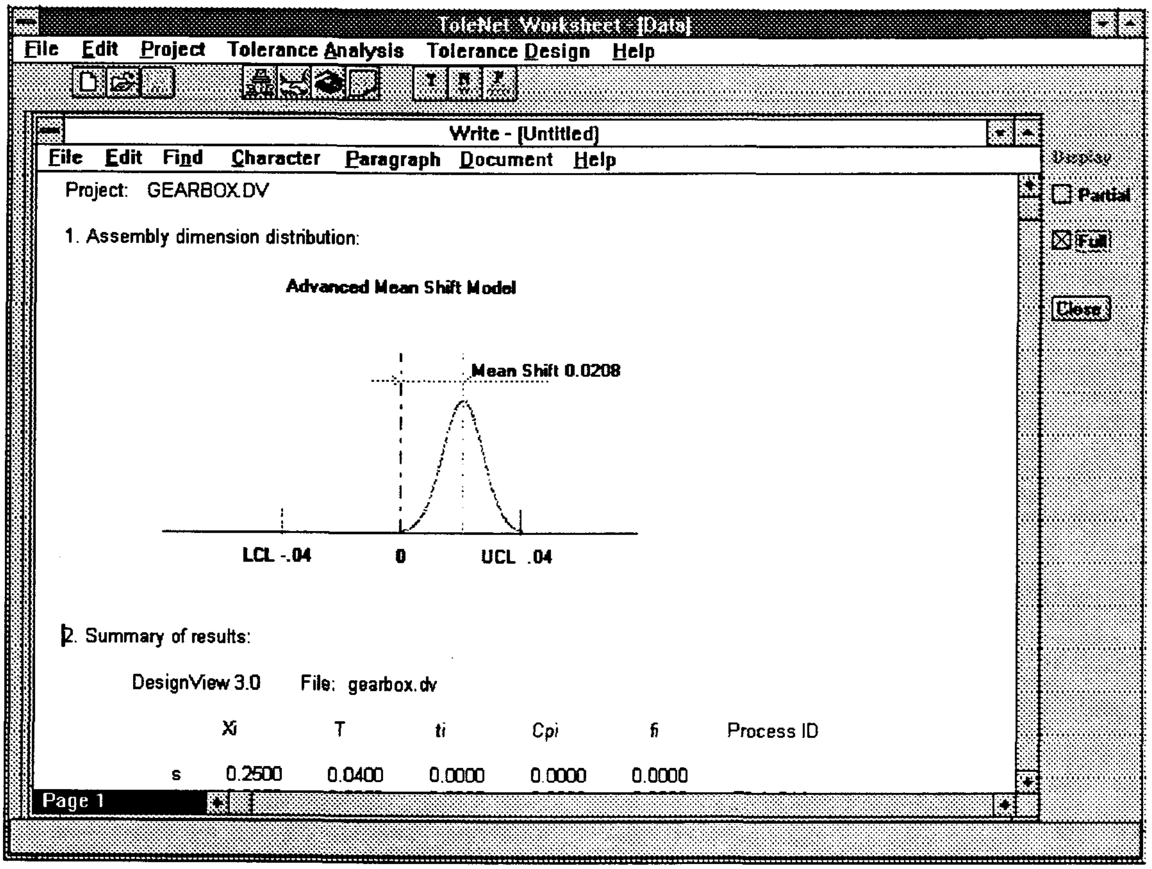


**Figure 5.9 Integrated Word Processor**

# Chapter 6 Conclusions and Recommendations

In this chapter, an overview is given of the important contributions made by this research to tolerance analysis research area. Several suggestions are made regarding further research possibilities in tolerance analysis modeling and software system development.

## 6.1 Research Contributions

Process mean and process capability are the two most important parameters used to describe part dimension distribution realized by a specific manufacturing process. The assembly tolerance analysis model proposed in this thesis incorporates these two factors for tolerance analysis so that the product designer can assign part tolerances based on real process capabilities under a desired assembly AQL. The model also allows adjustment and control of part dimension mean shift and process spread within the tolerance specification based on desired assembly AQL at manufacturing. This will help in bridging the gap between design and manufacturing.

The proposed model can be used to:

1. Verify the desired assembly AQL when component dimension mean shifts exist;

2. Consider individual process capability by adjusting the capability index $C_p$ when parts are randomized before assembling;

3. Provide information for selecting processes and for process planning;

4. Adjust control of process mean and process spread;

5. Consider dynamic characterization of the individual process by using dynamic process capability indices;

6. Provide the link between early stage design and later manufacturing in a concurrent product development environment.

The computer program described in this thesis has been developed to assist in the performance of part and assembly tolerance analysis concurrently with CAD modeling while making use of a manufacturing process database. The user has access to several commonly used assembly tolerance models as well as the new model developed in this thesis. The system has been developed to take advantage of multitasking feature of Windows, and uses Dynamic Data Exchange for integrating tolerance analysis models with a CAD modeling program and a manufacturing database. Integrated together, they form an integrated tolerance analysis and design environment. The tolerance analysis module itself can be easily planted into a larger concurrent product development environment that uses a similar mechanism of integration.

## 6.2 Recommendations for Further Research

The topic investigated in this thesis is broad and provides many possibilities for further research. The following is a list of research recommendations which are important to the development of an integrated tolerance analysis system.

### 6.2.1 Application of tolerance analysis model to non-linear assemblies

The assumptions made in the developed tolerance analysis model on parts dimension distribution enabled consideration of tolerances based on process spread and mean shift. These assumptions need to be utilized for non-linear assembly problem. However, in a non-linear assembly tolerance analysis problem, the model for predicting assembly dimension distribution will no longer be valid without modifications. There are two problems: first, statistical summation will not be as simple as in linear case; second, the worst case summation of mean shift will not give the same safety margin on non-linear problems. A method for non-linear assembly tolerance analysis using new assumptions of parts dimension distribution needs to be developed.

### 6.2.2 Modification to Account for Systematic Causes of Process Mean Shift

The developed tolerance analysis model needs to be modified when considering systematic causes of process mean shift, like tool wear. Furthermore, the possibility of considering dynamic process capability indices for assigning tolerances to part dimensions needs to be further explored.

### 6.2.3 Cost Analysis Associated with Current Tolerance Analysis Model

The developed model readily suggests a cost estimation model for the assigned tolerance: a fixed cost associated with process natural tolerance and a variable cost associated with the mean shift factor. The validation of the suggested cost model and the algorithm of using it in tolerance design for an economically optimum solution needs to be explored.

### 6.2.4 Development of a Manufacturing Process Capability Database

A manufacturing database based on real process capability data needs to be developed. There is a great deal of difficulty in collecting data on the behavior of manufacturing processes.

### 6.2.5 Implementation of System Integration for a Workgroup

The system can be expanded into network environment using controlled DDE operation for sharing data and may be used at a workgroup level.

### 6.2.6 More Design Tools and a Design Process Management Module

Additional tools need to be included in the current system to broaden the capability of the current system such as the sensitivity analysis (this can also be done using the capability of the integrated CAD modeling program), and optimization concerning different objectives and process planning. A better design management tool is needed to assist the user in choosing a design optimization procedure.

### 6.2.7 A Generically Independent Local Database

Structurally, the developed system needs a better generically independent local database and a management tool for sharing by different modules.

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# APPENDICES

# Appendix A

## Relationship between Mean Shift Factor $m_i$ and Dynamic Process Capability Indices $C_{pk}$ and $C_{pm}$

### 1. Process Capability Index $C_{pk}$

$C_{pk}$ is defined as [Kane, 1986]

$$C_{pk} = \min\{\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\}$$

where USL and LSL are the tolerance specification limits, $\mu$ is process mean and $\sigma$ is process standard deviation. Denote the midpoint of tolerance specification range as

$$\mu_m = \frac{(USL+LSL)}{2}$$

Then the process mean shift from $\mu_m$ is

$$S = | \mu_m - \mu |$$

Let

$$m = \frac{S}{T} = \frac{| \mu_m - \mu |}{\frac{USL - LSL}{2}}$$

then The $C_p$ adjusted by mean shift factor m is

$$C_{pk} = C_p(1-m)$$

or

$$m = 1 - \frac{C_{pk}}{C_p}$$

## 2. Process Capability Index $C_{pm}$

$C_{pm}$ is defined as [Chan 1988]

$$C_{pm} = \frac{USL-LSL}{6\sigma'}$$

where

$$\sigma' = E(X - \mu_T)$$

and $\mu_T$ denotes the target value of the process.

Since $\sigma'^{\,2} = E[(X-\mu)]^2+(\mu-[USL-LSL])^2$ and $\sigma^2 = E(X-\mu)^2$ , it follows that

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2+(\mu-\mu_T)^2}} = \frac{C_p}{\sqrt{1+\frac{(\mu-\mu_T)^2}{\sigma^2}}}$$

or

$$\frac{C_p^2}{C_{pm}^2} = 1 + \frac{(\mu-\mu_T)^2}{\sigma^2}$$

Notice that $S = |\mu - \mu_T|$ then $1 + \frac{(\mu-\mu_T)^2}{\sigma^2} = 1 + \frac{S^2}{\sigma^2} = 1 + (\frac{3S}{T}\frac{T}{3\sigma})^2$

and $\frac{S}{T} = m$ , $\frac{T}{3\sigma} = C_p$ , thus $\frac{C_p^2}{C_{pm}^2} = 1 + 9C_p^2m^2$ , or

$$m = \frac{1}{3}\sqrt{\frac{1}{C_{pm}^2} - \frac{1}{C_p^2}}$$

**3. The relationship between $m_i$ and $f_i$**

From equation 3.1, $f_i = \dfrac{S_i}{T_i - t_i}$, or rewriting as $\dfrac{1}{f_i} = \dfrac{T_i - t_i}{S_i} = \dfrac{T_i}{S_i} - \dfrac{t_i\, T_i}{S_i\, S_i}$

notice that $\dfrac{T_i}{t_i} = C_{P,i}$, then

$$f_i = \frac{m_i}{1 - \dfrac{1}{C_{p,i}}} \qquad \text{or} \qquad f_i = \frac{m_i}{1 - C_i}$$

Appendix B

# ToleNet User's Guide

## Contents

# List Of Figures

# Document Conventions

This user's guide uses the following typographic conventions:

| Example of convention | Description |
|---|---|
| System Setting | Name of menu item or command button, and the name of program window appear with initial letter capitalized. |
| Fit Type | This font is used for the text labels displayed in windows. |
| README.TXT | Words in all capital letters indicate file names. |
| ENTER | Small capital letters are used for the names of keys and key sequences. |
| **Type** | Word's you're instructed to type appear in bold. |

Chapter 1

# Introduction to ToleNet

Welcome to ToleNet for Windows, a program for assembly tolerance analysis and design.

ToleNet can aid you to perform tolerance analysis and design concurrently with CAD modeling, and discover potential manufacturing and assembly problems. ToleNet features a fully graphical user interface for the ease of use. It can be used in conjunction with other programs under Microsoft Windows to form a design system you want.

This chapter shows you how to set up ToleNet on your computer and how to get started.

## Setting Up

You install ToleNet on your computer using the program SETUP.EXE from the distribution disk. The setup program will install ToleNet itself to the hard disk of your computer.

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**Important** You cannot simply copy files from the distribution disk to your hard disk and run ToleNet. You must use the Setup program, which decompresses and installs the files in appropriate directories.

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## Before You Run Setup

Before you install ToleNet , make sure that your computer meets the minimum requirements and that your ToleNet distribution disk includes the required files:

### Check the Hardware and System Requirements

To run ToleNet in connection with CAD program, the minimum system requirements are:

- Any IBM-compatible machine with a 80286 processor or higher
- A hard disk.
- A 5 1/4" or 3 1/2" floppy drive.
- A SuperVGA or compatible display.
- One megabyte of memory in addition to run CAD program.
- A mouse.
- Microsoft Windows 3.1 or later in enhanced mode.

### Check the Distribution Disk

The distribution disk should include following files:

- tolenet.ex_
- setup.ex_
- install.ex_
- swtd.dg_
- swtd2.dg_
- swtd3.dg_
- swtd4.dg_
- swtd5.dg_
- swtd6.dg_
- cmdialog.vb_
- grid.vb_
- threed.vb_
- ddeml.dl_
- pdx110.dl_
- ver.dl_
- setup.1_
- gearbox.da_
- readme.txt
- commdlg.dl_
- msaes110.dl_
- msajt110.dl_
- vbdb300.dl_
- vbrun300.dl_
- share.ex_
- gearbox.d_
- process.md_

**Read the README.TXT file**

The README.TXT file lists most recent changes to the ToleNet which are not documented in this user's guide. To read the file, double-click README.TXT in the File Manager, or use the **Type** command in MS-DOS.

**Running Setup**

When you run the Setup program, you'll set a path for ToleNet.

To start Setup

1. Insert Disk in drive A.
2. From the File menu of the Program Manager or File Manager, choose Run.
3. Type **a:setup**
4. Follow the Setup instructions on the screen.

## Getting Started

This user's guide assumes you know how to use the CAD program for assembly modeling and the basic techniques to move around Windows. To know the techniques on how to use CAD program and Windows, please consult the relevant documentation.

### How this User's Guide is Organized

This user's guide includes eight chapters:

- Chapter 1: Introduction to ToleNet.

- Chapter 2 leads you to get around the ToleNet and shows the major structure of the program.

- Chapter 3 explains how to set up the integrated program environment for tolerance analysis and design.

- Chapter 4 explains how to edit working data to prepare for tolerance analysis using Data Editor.

- Chapter 5 explains how to choose a proper tolerance analysis model and perform tolerance analysis

- Chapter 6 explains how to use ToleNet to design part tolerances to meet the assembly tolerance specification

- Chapter 7 explains how to use ToleNet with a CAD program and using dynamic data exchange(DDE) to transfer data between CAD drawing and ToleNet program.

- Chapter 8 explains how to integrate a word processing program into ToleNet and use it to write a report.

### Sample Applications

A sample application to use ToleNet with DesignView 3.0 to perform tolerance analysis on a gear box problem has been included in distribution disk in directory \SAMPLE. In order to run this sample application, you must first install DesignView 3.0 on your computer.

## Technical Support

For technical support and reporting any bugs you may encounter, please contact Bryan Qian, Department of Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR 97330, or send E-Mail to qianx@conan.ie.orst.edu or XiaonongQ@aol.

Chapter 2

# Getting Around ToleNet

When you run the ToleNet Setup program, Setup automatically creates a new program group and new program items for ToleNet in Windows. You are then ready to start ToleNet from Windows.

## Starting ToleNet

To start ToleNet from Windows, double-click the ToleNet icon. You can also start ToleNet from either the File Manager or MS-DOS prompt.

When you first start ToleNet, you see the interface of the program, as shown in Figure 2.1. This is the main interface window of the program.

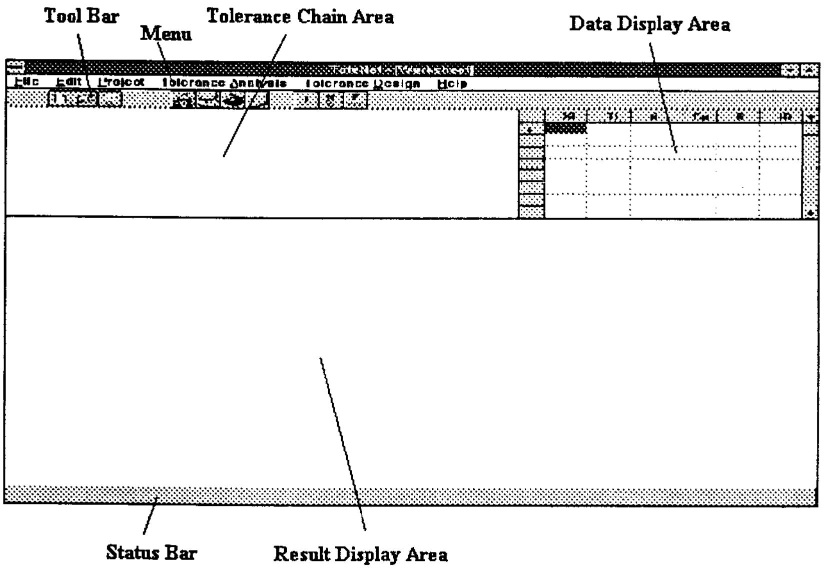
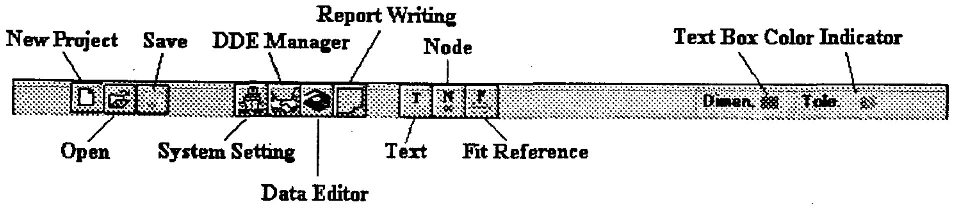
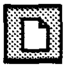
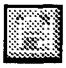
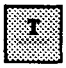
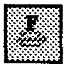



**Figure 2.1 The ToleNet Program Interface**




**Toolbar** Provides quick access to commonly used commands in the program environment. You click an icon on the toolbar once to carry out the action represented by that icon

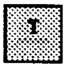
| Icon | Action | Menu equivalent |
|---|---|---|
|  | Start a new project | New command on the File menu |
|  | Open an existing project | Open command on the File menu |
|  | Save the current Project | Save command on the File menu |
|  | Open System Setting window | System Setting command on Project menu |
|  | Open DDE Manager window | DDE Manager command on Project menu |
|  | Open Data Editor window | Data Editor command on Project menu |
|  | Open word processor for report writing | Report Writing command on Project menu |
|  | Show or hide text boxes associated with tolerance chain | Text command on submenu Tolerance Chain on Tolerance Design menu |

| | | |
|---|---|---|
|  | Open editor for specifying relationships between adjacent dimensions | Node command on submenu Tolerance Chain on Tolerance Design menu |
|  | Show the reference table for different fit types | Fit References command on Tolerance Design menu |

**Data Display Area** Data display area is a grid consists of six columns. The data displayed are labeled by

- Xi — value of nominal dimension i
- Ti — value of tolerance on dimension i
- ti — value of process natural tolerance for dimension i
- $C_{p,i}$ — value of process capability for dimension i
- fi — mean factor value for dimension i
- ID — process ID number for dimension i

The data for assembly critical dimension are displayed in the first row.

**Tolerance Chain Area** This area is for displaying the graphical representation of tolerance chain. The tolerance chain will only be displayed after you have edited the data for the project or opened an existing project data file. There are some text boxes associated with tolerance chain. They are usually hidden unless you use Text command from submenu Tolerance Chain on Tolerance Design menu, or click on  icon from the toolbar.

**Result Display Area** This area is for displaying the results of tolerance analysis and several other tools used for tolerance design. They are usually hidden unless you use relevant command to show them. This will be explained later.

## Running the Sample Project

Included in distribution disk there is a sample project file GEARBOX.DAT. Click on Open from File menu, a dialog box will show on screen as shown in Figure 2.2. Choose GEARBOX.DAT from directory \SAMPLE, and click on OK, the project Gearbox will be opened. You can then move around to explore the ToleNet program.

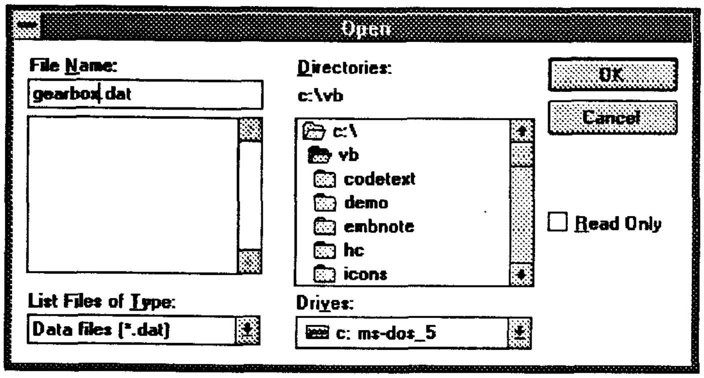



**Figure 2.2 Dialog Box for File Open**

Chapter 3

# Setting Up An Integrated Tolerance Analysis System

ToleNet is intended to be used in an integrated design environment for tolerance analysis at product design stage. It can be linked to a CAD drawing file via dynamic data exchange(DDE), and directly access a manufacturing process database.

The integrated tolerance design and analysis system is setup through the window System Setting as shown in Figure 3.1. To specify the CAD program, drawing file and manufacturing database table, You simply fill up the text boxes in each group area.

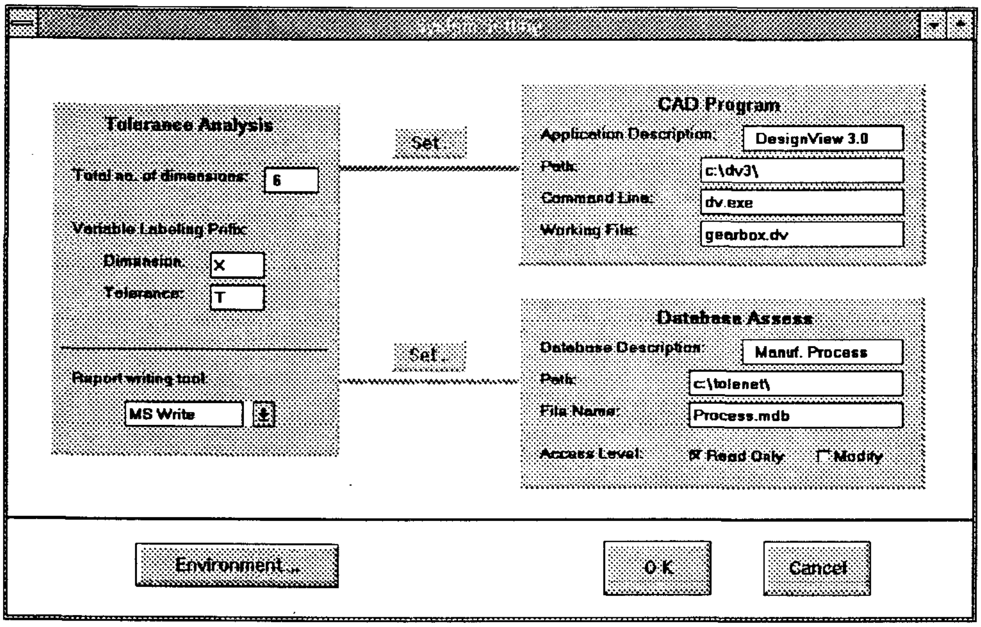



**Figure 3.1 System Setting Window**

To setup DDE connection between ToleNet and CAD drawing, open the window DDE Setting by click on button Set..., and fill up the appropriate text boxes as shown in Figure 3.2.

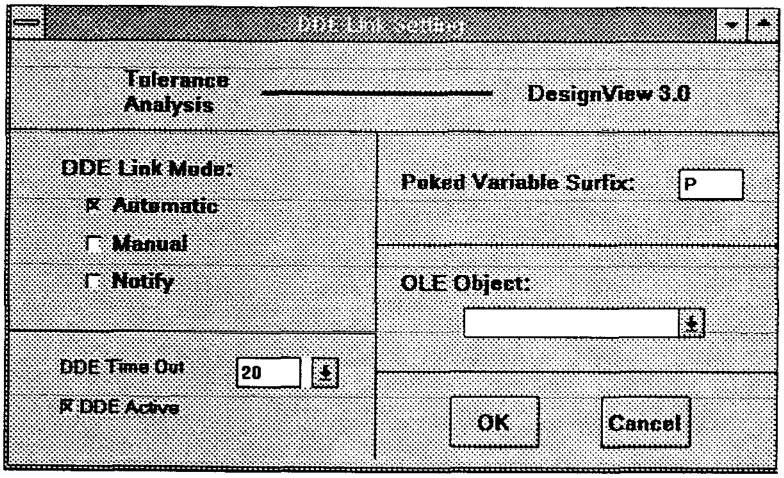



**Figure 3.2 The Window DDE Setting**

To setup whether or not to embed word processor and CAD program inside ToleNet and the maximum number of dimensions, access the window Environment as shown in Figure 3.3. By default, the maximum number of dimensions is 20 and the word processor is embedded. The default word processor is MS Write.

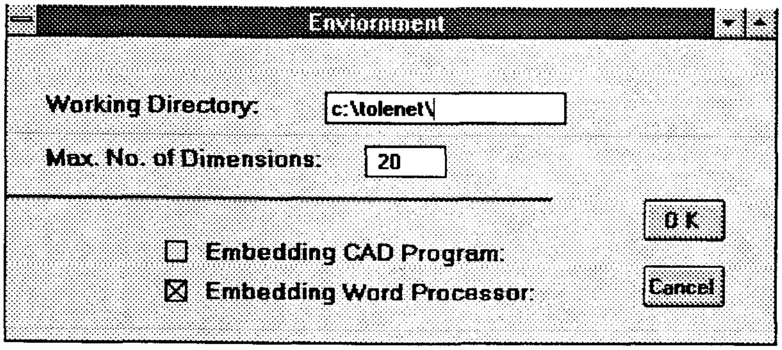



**Figure 3.3 Window Environment**

The system setup does not have to be done at the beginning of the project. The program will prompt you to specify the system information needed during the project. However, starting project in a planned way will help you experience less trouble later.

Chapter 4

# Editing Working Data

You prepare all the data needed for preforming tolerance analysis in the window Data Editor as shown in Figure 4.1.

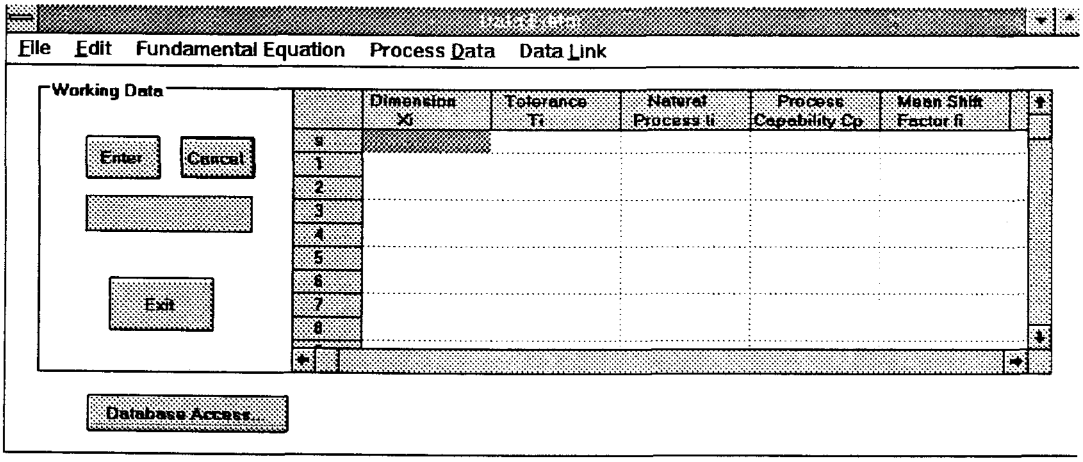



**Figure 4.1 Window Data Editor**

## Add Rows and Columns

If you have specified total number of dimensions in System Setting, the Data Editor will display the same number of rows in a spreadsheet like editor. If you have not specified total number of dimensions, the grid will display only one row. You can add any number of rows by selecting Add Rows from the menu Edit. Also, depending on what tolerance analysis model you plan to use, You can choose either three columns or six columns from the menu Edit. If three columns are displayed, the first column is for dimension values($X_i$), the second column is for tolerance values($T_i$), and the third column is for process ID(ID). If six columns are displayed, the sequence of columns for data entry are: Dimension($X_i$), Tolerance($T_i$), Process Natural Tolerance($t_i$), Process Capability($C_{p,i}$), Tool and Process ID(ID).

The first row of data grid is always entered as the assembly critical dimension. ToleNet gives it a label s.

## Orders of Data Entries

You must specify the number of rows as the same number as in assembly model. The program uses the number of rows you chose in Data Editor to determine the total number of tolerances in the assembly tolerance analysis. Furthermore, you must specify the order of the rows in the same order that the tolerance chain is formed. The program generates assembly tolerance chain in the order you entered the data in Data Editor.

## Entering Data from Text Boxes in Tolerance Chain

After a tolerance chain is generated, you can edit dimension and tolerance values in the text boxes attached to the tolerance chain as shown in Figure 4.2. In the window ToleNet Worksheet, select Tolerance Chain from the menu Tolerance Design and then submenu Text. A check mark will show in front of menu Text to indicate whether it is checked. If it is checked, the text boxes associated with tolerance chain are visible, otherwise they are hidden. On the toolbar of the main window, a color indicator shows the colors associated with text boxes for dimension values or tolerance values. As you change values in the text boxes, the data will also be displayed in the datagrid area to show the changes you made.

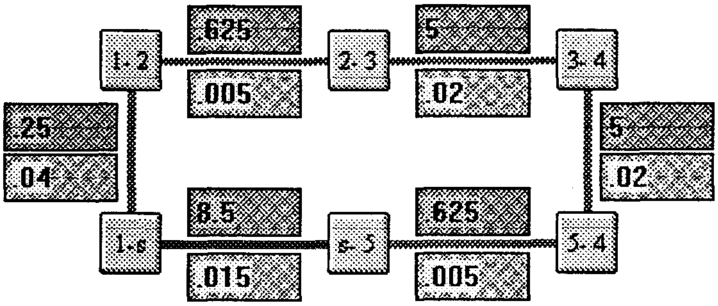



**Figure 4.2 Data Entry from Text Boxes in Tolerance Chain**

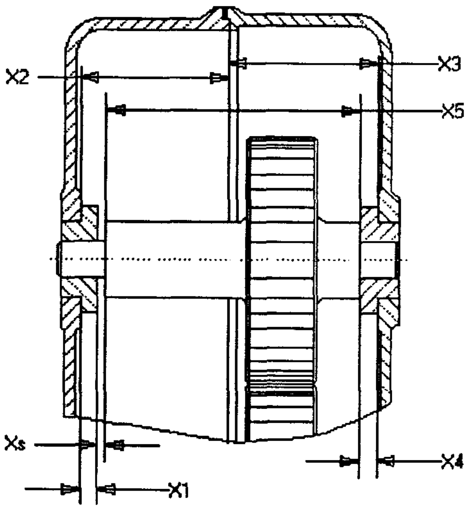
Chapter 5

# Performing Tolerance Analysis

ToleNet currently only supports tolerance analysis on dimensional tolerances with linear assembly problem. The techniques involved in non-linear assembly problem and geometrical tolerances are much more complex and are not well studied so far. You can refer to relevant documents for more information on this issue, which are usually scattered in engineering journals.

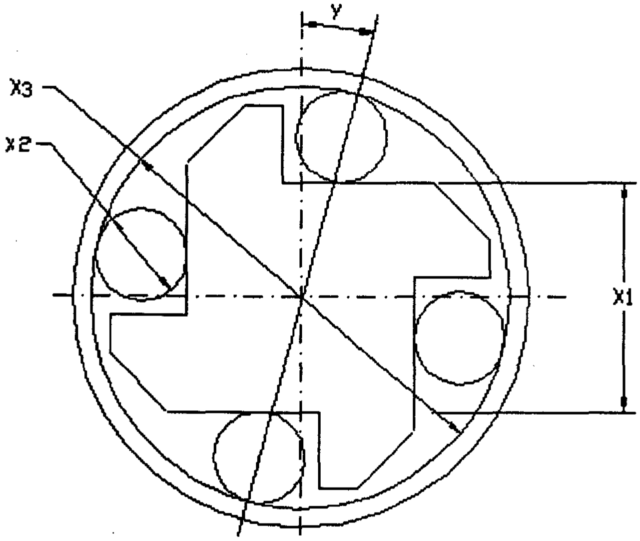
## Linear Assembly Problem

Linear assembly problem is the problem in which the assembly critical dimension is a linear function of parts dimensions. For Example, in Figure 4.1, the gearbox axial assembly is a linear problem, but in Figure 4.2, the problem is nonlinear. In practice, majority of assembly problems are linear problems, or can be reasonably simplified as linear problems. However, there are many cases that a nonlinear problem must be solved. You can refer to relevant articles for more information about non-linear tolerance problems.




$$X_s = -X_1 + X_2 + X_3 - X_4 - X_5$$

**Figure 5.1 Linear Tolerancing Problem**




$$y = \arccos\left(\frac{x_1 + x_2}{x_3 + x_2}\right)$$

**Figure 5.2 Non-Linear Tolerancing Problem**

## Tolerance Analysis Model

Tolerance analysis model is a mathematical model for predicting assembly critical dimension tolerance based on part dimension tolerances. Depending on how the part dimension tolerances are modeled, there are several different tolerance analysis models in existence. ToleNet program has included four most commonly used tolerance analysis models:

- Worst Case model
- Root Sum Squares model
- Motorola Six Sigma model
- Advanced Mean Shift model

Part dimensional tolerances can be presented in many formes. The most commonly used specification for dimensional tolerance in mechanical design is high/low tolerances, which is written as $^{+\text{ high tolernce}}_{-\text{ low tolernce}}$. The high tolerance and low tolerance need not to be equal to form a symmetrical tolerance zone. However, in ToleNet, only a symmetrical tolerance zone specification is used. The tolerance zone is specified as $\pm$tolerance. Any non-symmetrical situation can be easily transformed into a symmetrical form.

## Worst Case Model

Worst Case model is expressed as

$$T_{assem} \leq \Sigma T_i$$

where $T_{assem}$ is the sum tolerance on the assembly dimension and $T_i$ is tolerance for part dimension i. It assumes that each part dimension in the assembly loop has the maximum value, therefore forms a worst case. If at this worst case the accumulated assembly critical tolerances still meets the design specification, then the actual parts with dimensions produced within the tolerances specification will guarantee that the accumulated assembly critical dimension tolerance will meet the design specification with one hundred percent acceptance quality.

The Worst Case model gives a one hundred percent acceptance quality. But the part tolerances usually must be very small to meet the assembly critical dimension tolerance specification. The smaller the part tolerances, the higher the production cost.

To use Worst Case model, only the tolerances on each part dimension are needed.

## Root Sum Squares Model

Root Sum Squares model is expressed as

$$T_{assem} \leq \sqrt{\Sigma T_i^2}$$

where $T_{assem}$ is the sum tolerance on the assembly dimension and $T_i$ is tolerance for part dimension i. It assumes that each part dimension is normally distributed within the tolerance specification $\pm T_i$, with the mean at nominal dimension value and standard deviation equal to one third of one-sided tolerance $T_i/3$, and there will be 2.7 parts per one thousand out-of-tolerance. Likewise, the resulting assemblies will have 2.7 parts per one thousand out-of-tolerance. This corresponds to an acceptance rate of 99.73 percent. Compared with the Worst Case model, part tolerances in the Root Sum Squares model may be increased significantly, since they add as the root sum square.

To use the Root Sum Squares model, only the tolerances on each part dimension are needed.

## Motorola Six Sigma model

Motorola Six Sigma model is expressed as

$$T_{assem} \le Z\sqrt{\Sigma\left(\frac{T_i}{3C_{p,i}(1-f_i)}\right)^2}$$

where $f_i = \frac{mean\ shift}{T_i}$. Motorola's model is in the form of the Root Sum Squares model but uses an effective standard deviation to account for the process dispersion which may be caused by uncontrollable random factors and/or inevitable systematic factors like tool wear. In Motorola's model,

$$\sigma_{e,i} = \frac{T_i}{3C_{p,i}(1-f_i)} \qquad \text{and} \qquad C_{p,i} = \frac{USL-LSL}{6\sigma_{p,i}}$$

where $C_{p,i}$ is the process capability index, $f_i$ is the mean shift factor and $T_i = \frac{UCL-LCL}{2}$.

To use Motorola Six Sigma model, you need to prepare tolerance specification $T_i$ for each part dimensions, process capability index $C_{p,i}$ with which the part dimension is to be machined, and the process mean shift factor $m_i$. For detailed information on how to use Motorola Six Sigma model, please refer to relevant articles.

## Advanced Mean Shift model

The Advanced Mean Shift model is expressed as

$$T_{accum} = \Sigma f_i(1-C_i)T_i + (\frac{Z}{3})\sqrt{\Sigma(C_iT_i)^2}$$

where $S_i$ is the mean shift, $f_i$ is the estimated mean shift factor, and $C_i$ is a factor indicating how much the natural process tolerance covers the tolerance specification.

$$f_i = \frac{S_i}{T_i - t_i} \qquad \text{and} \qquad C_i = \frac{1}{C_{p,i}}$$

When fi = 1, mean shift is at its maximum value ($T_i$ - $t_i$) within the tolerance specification; when fi = 0, there is no mean shift; when fi > 1, there will be severe rejection rate in final assembly. Notice here fi is defined in proportion to (Ti-ti) rather than Ti as in Motorola Six Sigma model, and it represents the difficulty to control the mean shift rather than simply the mean shift value. $C_{p,i}$ is the same as defined in Motorola's model.

The AQL for assembly, $AQL_{assem}$ may be given as

$$AQL_{assem} = 1 - \Phi(\frac{T_{assem} - \mu_{accum}}{\sigma_{accum}})$$

where $\mu_{assem}$ and $\sigma_{assem}$ are given by

$$\mu_{accum} = \Sigma f_i(1-C_i)T_i$$

$$\sigma_{accum} = \frac{1}{3}\sqrt{\Sigma(C_iT_i)^2}$$

The Advanced Mean Shift model gives only the accumulated tolerance, not the assembly tolerance, $T_{assem}$, and $AQL_{assem}$ depends on the expected value of accumulated dimension and $\sigma_{accum}$. $T_{assem}$ has to be chosen to achieve the required AQL.

To use the Advanced Mean Shift model, you need to prepare the data for part tolerance $T_i$ , process capability index $C_{p,i}$ and estimated mean shift factor $f_i$ .

## Selecting the Tolerance Analysis Model

The four available tolerance analysis models have different complexity. Depending on the data you have or the requirement of the design, you can choose the model accordingly.

1. Generally, Worst Case model will give the safest results.

2. None of the statistical models can be expected to give reasonable accuracy if there are less than five parts in the assembly. The same is true when there are only small amount of assemblies to be produced. The exact number of parts needed for using statistical tolerance model varies depending on the actual situation, but in general, it should be larger than twenty.

2. If mean shift model is to be used, a larger mean shift factor will give safer results. Unless you have adequate data to show that the mean shift of the process output is well controlled, the minimum value for mean shift should be larger than 0.5.

3. If no data on mean shift and process capability are available, the Motorola model can be used instead of Root Sum Squares model for better results. The effective deviation in Motorola Six Sigma model can be modified to achieve safer results than the Root Sum Squares model.

# Chapter 6
# Tolerance Design

Until satisfactory result is obtained, you need to re-edit data and perform tolerance analysis again. To adjust or assign proper tolerance to a specific part dimension you need more information on how to choose the tolerance value. ToleNet has provided several useful tools to help you in this process.

## Specifying Part Dimension Relationship

It is very important to understand the relationship between adjacent parts.

The relationship between mating parts can be classified in three categories: **Fit**, Against, and Parallel. **Figure** 6.1 explains these situations.

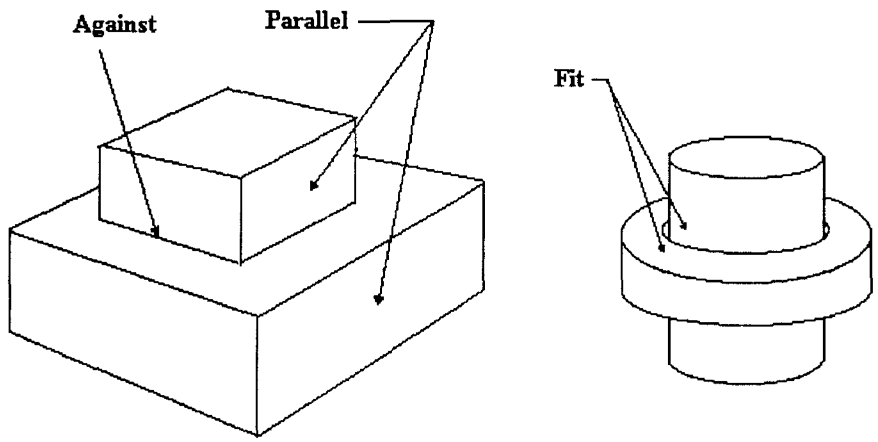



**Figure 6.1 Part relationships**

To specify part relationship, select Node from the menu Tolerance Design, or click on the node of the tolerance chain, a frame will appear at the lower left portion of the window ToleNet Worksheet. If you select Fit, an additional selection box will let you select the fit type. On the bottom of the frame, definitions and help information are displayed accordingly to help you understand the choice you may have made. After you have selected part relationship, the initial letter of selected relation type will be displayed in the node of tolerance chain. To specify a specific node in tolerance chain, you must first click on the node to make the node a current node.

## Selecting Machining Processes

Each dimension you designed is to be finally realized through a manufacturing process. The distribution of realized dimension depends on the process used for making this dimension. Therefore, in order to describe the process behavior needed in tolerance analysis, you need to specify process used for realizing the specific dimension.

ToleNet is able to directly access a manufacturing database to provide you with the information on process parameters. Select Database Access..., the database records are displayed at the bottom of the window Data Editor as shown in Figure 5.3. You can select a process either from a drop down list box or from the menu Process.

The database included in ToleNet distribution disk includes milling, turning, surface grinding, cylinder grinding, boring and drilling processes, that are most commonly used in machining. For each process, data records are collected according to different tools used, different size ranges and different precision grades. Each record is identified by an ID number. You can enter this ID number into the datagrid which will then be saved into the global working data for the project. The record item collected for each process is shown in Figure 6.2.

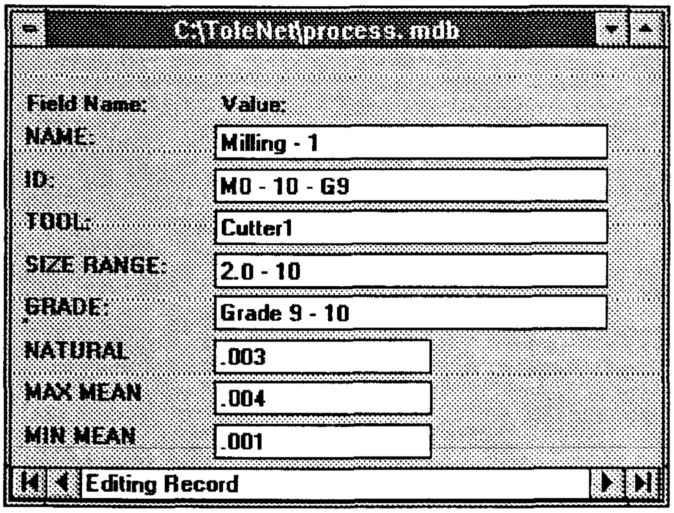



**Figure 6.2 Manufacturing process database records**

## Process Capability

Process capability index $C_p$ is defined as

$$C_p = \frac{\textit{allowable process spread}}{\textit{actural process spread}} = \frac{USL-LSL}{6\sigma_p}$$

where $6\sigma_p$ is actual process spread, often expressed as $\pm 3\sigma_p$. The one-sided spread ($3\sigma_p$) is also called natural process tolerance. $C_p$ is used to judge whether or not the process selected is capable of realizing the specified tolerances. The higher the $C_p$ is , the more capable the process is and the fewer out-of-tolerance parts are expected. A capable process ($C_p = 1$) with underlying stable normal distribution will in theory result in 0.27% of parts out-of-tolerance. A minimum of $C_p = 1.33$ is usually recommended. However, when $Cp > 2$, the gain of quality is insignificant.

## Process Mean Shift

Process spread is not always centered. In practice, the mean of a process output always drifts away from the target value. The process mean shift is a dominated factor to affect the result of tolerance analysis.

In tolerance analysis, process mean shift is addressed by mean shift factor. There are two different mean shift factor definitions. One is specified in proportion to the tolerance specified, as in Motorola Six Sigma Model. Another one is specified in proportion to the maximum mean shift allowed, as in Advance Mean Shift model. When mean shift is defined as in proportion to the tolerance, it represents the value of the mean shift; when it is defined as in proportion with the maximum mean shift, it represents the difficulty of controlling mean shift.

## Tolerance Specification

The purpose of tolerance analysis is to verify whether tolerance values assigned to part dimensions will result an assembly critical dimension within the specified tolerance specifications when the parts are assembled. Generally, the assembly critical tolerance is decided for assembly performance. It is a preset requirement for tolerance analysis and design to assure.

The part tolerances can be initially assigned based on ANSI standards, which gives rough guidance on where you should start with. After the tolerance values on each part dimension are assigned, you can use an adequate tolerance analysis model to verify whether or not they will meet the requirement of assembly tolerances. The reassessment of tolerance value should be based on actual process capability and allowed mean shift, if it is possible. As a general rule, the process capability should be lager than 1.33 and best if larger than 2.

## Chapter 7

# Working with CAD Program

CAD Program is integrated in such a way that the data of dimensions and tolerances can be imported in ToleNet and then be exported from ToleNet to CAD drawing dynamically through DDE. In addition, if the CAD program supports object linking and embedding(OLE), the drawing can be embedded inside ToleNet for easy access for geometric modeling and editing.

All the DDE operation are managed in the window DDE Manager in ToleNet. You can open DDE Manager by selecting menu DDE Manager from menu Project in the window ToleNet Worksheet, or you can select submenu Data from CAD or from the menu Data in the window Data Editor.

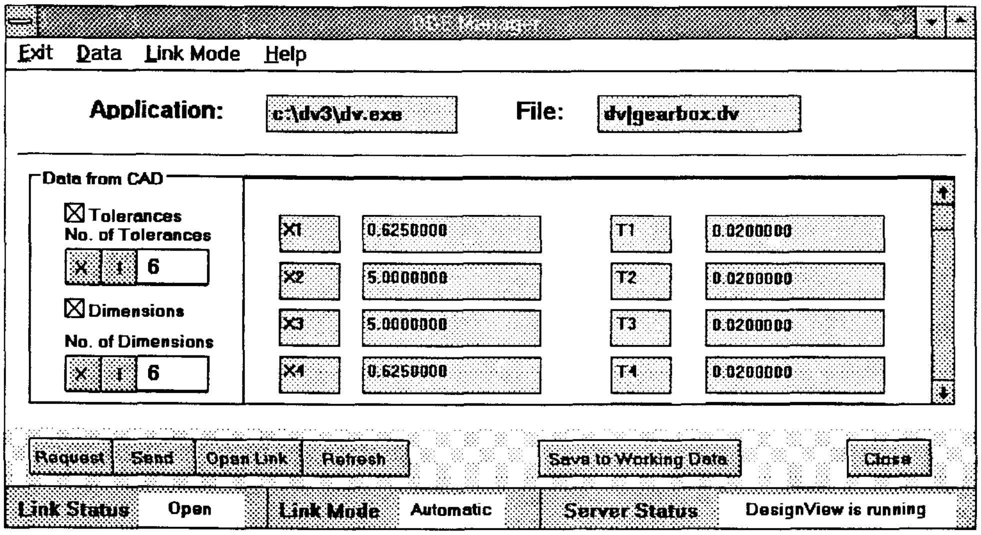



**Figure 7.1 DDE Manager**

## DDE Link Topic

Link Topic is the source where you want to transfer the data from. In window DDE Manager, it is specified in filed "File:". Different CAD program may use a different convention to specify Link Topic. For example, DesignView 3.0 use "D|*.D" as Link Topic, as shown in Figure 7.1, where "D is the name of executable file of main program, "*.D" is the name of the drawing file. A vertical slash "|" is put in between the "D" and "*.D". If you are using other CAD programs, consult your CAD program's user's guide for how to specify Link Topic.

You can fill up the "File" inside the DDE Manager, or if you specified DDE setting in window System Setting, the "File" field will automatically be filled with the proper Link Topic.

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**Important** You must make sure the Link Topic in the field "File" is correct or otherwise the DDE operation can not be performed.

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## DDE Link Item

Link Item is the data item in resource file that you wanted to link to other program. In our case, the Link Item may be a part dimension or tolerance. In most cases, if you want link dimension or tolerance to ToleNet, the Link Item is the variable name you used for labeling the dimension or the tolerance. Again, depending on the CAD program you are using, it may use a different way of labeling the variable for DDE operation. Consult the relevant document for detailed information.

In DesignView 3.0, dimensions and tolerances or any other variables can be labeled just as you would do when doing a math calculation. You give each variable a variable name. Then when you are referring to a variable name, you are referring to both the variable as an entity and its value. In Figure 7.2, the example shows how the dimensions and tolerances in a gearbox drawing are labeled.

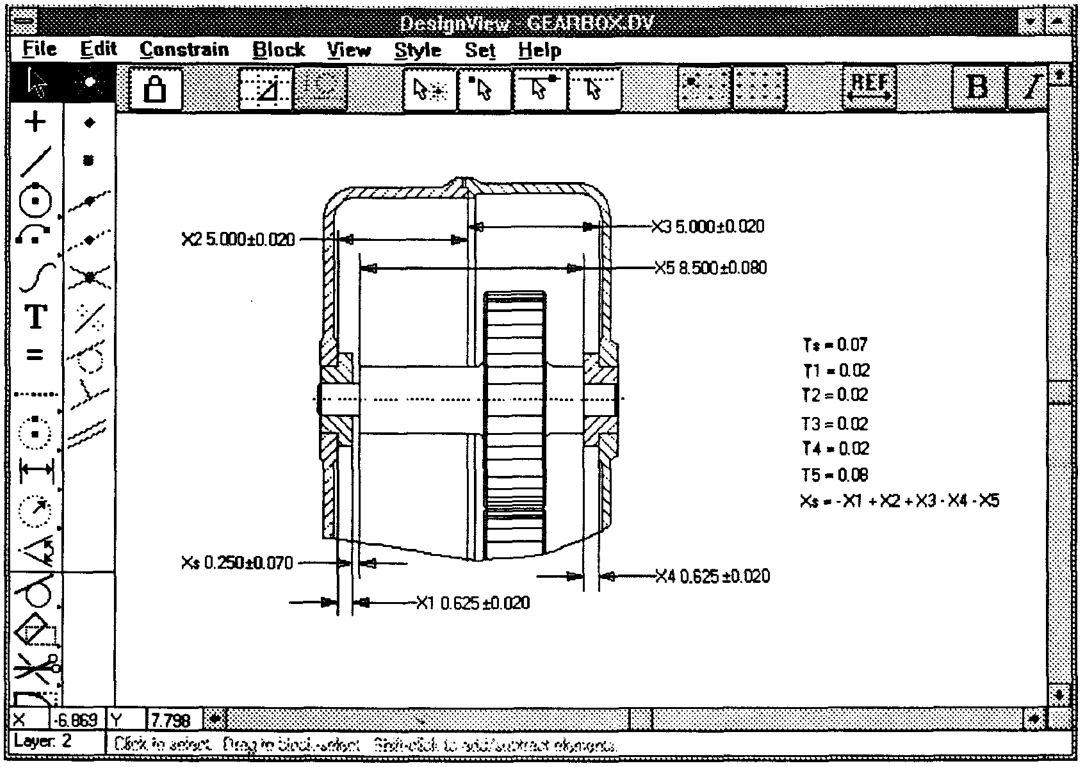


**Figure 7.2 Labeling Dimensions and Tolerances in DesignView Drawing**

## Importing Data from the CAD Drawing

Your CAD program must support DDE in order to be used with ToleNet for DDE data transfer.

Depending on the CAD program you are using, the detailed DDE operation procedure may vary slightly, but it should follow the same mechanism, since DDE is an industry standard.

In DDE Manager, there are two groups of text boxes for dimensions and for tolerances. You can specify the number of dimensions or tolerances you want to transfer from the CAD drawing. In each group of text boxes, the left column is for link item, the right column is for the data value of the item specified in link item. For example, if you want to transfer a tolerance value $T_1$ into ToleNet, then $T_1$ is the link item; you enter T1 in the text box on the left column.

After you have entered the Link Topic and the Link Items, choose Open Link from either the menu Data or the command button on the lower button bar. The value of the data item will be displayed in the text boxes on the right column. If you have not started the CAD program, ToleNet will ask you whether the CAD program should be started. If you choose "Yes", ToleNet will start the CAD program you have specified in the Field "CAD Name", and then you should open the drawing file. Then you can choose Request from button bar or from the menu Data to get the data from CAD drawing.

ToleNet is capable of transferring multiple data items. However, if any of the link items is not properly specified, a massage will be show on the screen to tell you that an error happened while performing DDE operation, and the data items have not been transferred. You need to correct the false items and perform DDE operation again.

After you have transferred data from the CAD drawing, select Save To Working Data, the data value will be saved to global working data. You can go back to the Data Editor to edit them or go to ToleNet Worksheet to perform tolerance analysis.

# Exporting Data to the CAD Drawing

After you finished tolerance analysis, you can export the data back to CAD drawing by two ways:

- From in side ToleNet, poke the data back to CAD drawing.
- From inside CAD drawing, import data from ToleNet program

## Poke Data Back to CAD Drawing

Open DDE Manager, and perform the same process as you did in importing data from CAD drawing, specify the link items, and open the DDE link. Notice that when you established the link to CAD drawing file, the data values displayed in the text boxes or the right column are the values copied from the CAD drawing. To get the modified data from the results of tolerance analysis, you need to replace those values with the values in ToleNet's working data. Choose Get Working Data from the menu Data or button bar, the values in the text boxes on the right column will now be replaced with the new values. Click on Send on button bar (or from the menu Data), the data can now be poked back to the CAD drawing.

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**Note** You must first establish link to CAD drawing before you can send the data back to CAD drawing. The link you have established when you import data from CAD drawing is terminated when you exit the DDE Manager.

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** When you work with DesignView 3.0, you must use a different variable name when poking the data back to CAD drawing. For example, if you used T1 as the label for tolerance 1, you can import the value of T1 into ToleNet by using T1 as a link item. But when you poke back the T1 from inside ToleNet to DesignView 3.0, a DesignView error massage "Can not solve for external reference" will show on screen. This is due to a bug existing in DesignView 3.0 (For more information, please read the DesignView 3.0 README.TXT file). You can work around this problem by using a separate variable. For example, in the last example, you can use a variable $T_1P$, assign $T_1 = T_1P$ from inside DesignView, then use $T_1P$ as the link Item to poke the data value of $T_1$ back to DesignView 3.0. Figure 7.3 shows an example of how the values of tolerance are poked back to the drawing gearbox.dv.

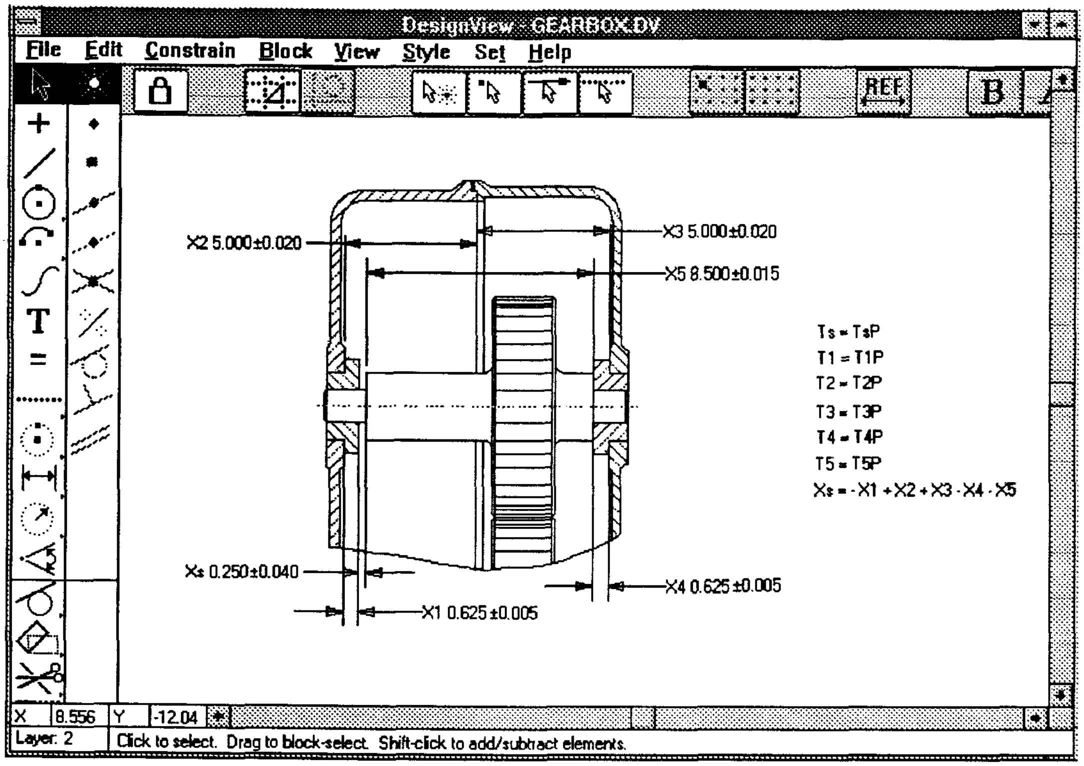


**Figure 7.3 Poke Tolerance Value Back to GEARBOX.DV**

**Importing Data into CAD from ToleNet**

ToleNet also supports DDE as a server. Therefore, you can import data from ToleNet into any program and from there you can initiate DDE operation.

The DDE server in ToleNet is the window DDE Manager. Its link topic name is "DDEmangr". All the text boxes in the window DDE Manager can be used as link items. However, the same two groups of text boxes are recommended for this purpose. In each group, the name for the text boxes on the left column are DimenText(Index) or ToleText(Index), and the name for the text boxes on the right column are DimenValue(Index) or ToleValue(Index), where Index = 0, 1 ,2, ... . For example, if you want to link data T1 in gearbox.d to T1 in DDE Manager, make sure the DDE Manager window is open, then from inside DesignView, edit equation "T1 = D|DDEmangr!ToleValue(0)", and now the value in the text box ToleValue(0) is copied into the drawing gearbox.dv. Please refer to your CAD program's documentation for more information on how to import data from other programs into your CAD drawing.

The differences between poking data back to CAD drawing and importing data from ToleNet into CAD drawing are:

1. With poke method, you can send multiple data item values back to the CAD drawing at once. You can edit the data before you poke them; while importing from ToleNet into CAD, you need a command for each item you want to link.

2. With poke method, after you have poked the data back to the CAD drawing, the DDE link between the DDE Manager and the CAD drawing file is closed upon exiting DDE Manager. If you want to poke data again, you

need to open the link again. This may require duplicated work but gives you the control on DDE operation, while importing from ToleNet into CAD, you initiate DDE link from inside the CAD. You can keep the link active so that whenever the data resource changes in DDE Manager in ToleNet, the linked data in CAD drawing will change dynamically. However, when you exit DDE Manager in ToleNet program, the link is closed. You will need to re-initiate DDE link from inside the CAD program when you need to get the data from ToleNet. This may not be as convenient as it sounds to be, depending on how the CAD program you are using handles the DDE initiation. For example, with DesignView 3.0, to re-initiate a same DDE link as we did before, you need to retype the command "T1 = D|DDEmangr!ToleValue(0)" because after the initial link is closed, the command will not re-initiate the link automatically.

## Embedding CAD Drawing into ToleNet

CAD program can be embedded in ToleNet so you can more easily access CAD drawing.

If the CAD program you are using supports object linking and embedding, you can embed the CAD drawing into the window ToleNet: CAD Viewer. If the CAD program you are using does not support OLE, you can embed it by setting the CAD window as the child widow of the window ToleNet: CAD Viewer. This feature is enabled only if you check the item Embedding CAD Program in the window Environment which is accessed from inside the window System Setting.

From the menu Embedding in the window ToleNet: CAD Viewer, set the embedding method. If the CAD is chosen to be embedded as a child widow, the whole CAD program will run inside the border of the window ToleNet: CAD Viewer. You can access all the functions of the CAD program just as you run it normally from Windows Program Manager. If you move ToleNet: CAD Viewer, the CAD program window will move accordingly. Figure 6.4 shows DesignView 3.0 embedded as the child window of ToleNet: CAD Viewer. If CAD is chosen to be embedded via OLE, you embed only portion of the drawing file into the window ToleNet: CAD Viewer. You can access CAD program by double clicking on the embedded drawing, and then the CAD program will start with the embedded drawing loaded. You can edit drawing and then exit the CAD program. The embedded drawing in the window ToleNet: CAD Viewer will show the changes of editing in the CAD program.

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**Important** If you embed the CAD drawing into the window ToleNet: [CAD Name], the DDE operation described above may not work properly.

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Chapter 8

# Writing Report on Results

ToleNet generated results include four parts:

1. Numerical values of dimensions, tolerances, process natural tolerances, process capabilities, process mean shift factors, process ID numbers and parts relationships.

2. Assembly reject rates, assembly critical dimension mean shift and the deviation of spread.

3. Graphical presentation of tolerance chain.

4. Graphical presentation of assembly tolerance distribution.

All the above results can be copied into Windows Clipboard and then be pasted into a word processor for report writing.

ToleNet itself does not have a text editor for writing a report, but rather provides the capability to embed a word processor into it for the same purpose so you can have the full power of a word processor.

## Selecting A Word Processing Program

You can use any word processing program that runs under Windows. Furthermore, you can embed it as a child program under ToleNet. This will help you to be able to easily switch back and forth from ToleNet to word processor or vise versa. In ToleNet System Setting, you can choose a word processor to be embedded, or you can choose not to embed word processor into ToleNet by un-checking "Embed Word Processor" from the window Environment. An embedded word processor works just the same as you would start it from the Program Manager separately.

## Using Clipboard to Copy and Paste Results

To copy results of tolerance analysis, you simply select the item from the menu Result, then from word processing program, paste it into report document. If you have embedded the word processor into ToleNet, you can access it by selecting Report Writing from the menu Project. Then you do not need to switch back and forth from ToleNet to Word Processor or from Word Processor to ToleNet. Figure 8.1 shows an embedded MS Write in the window ToleNet Worksheet, with the edited report of results.

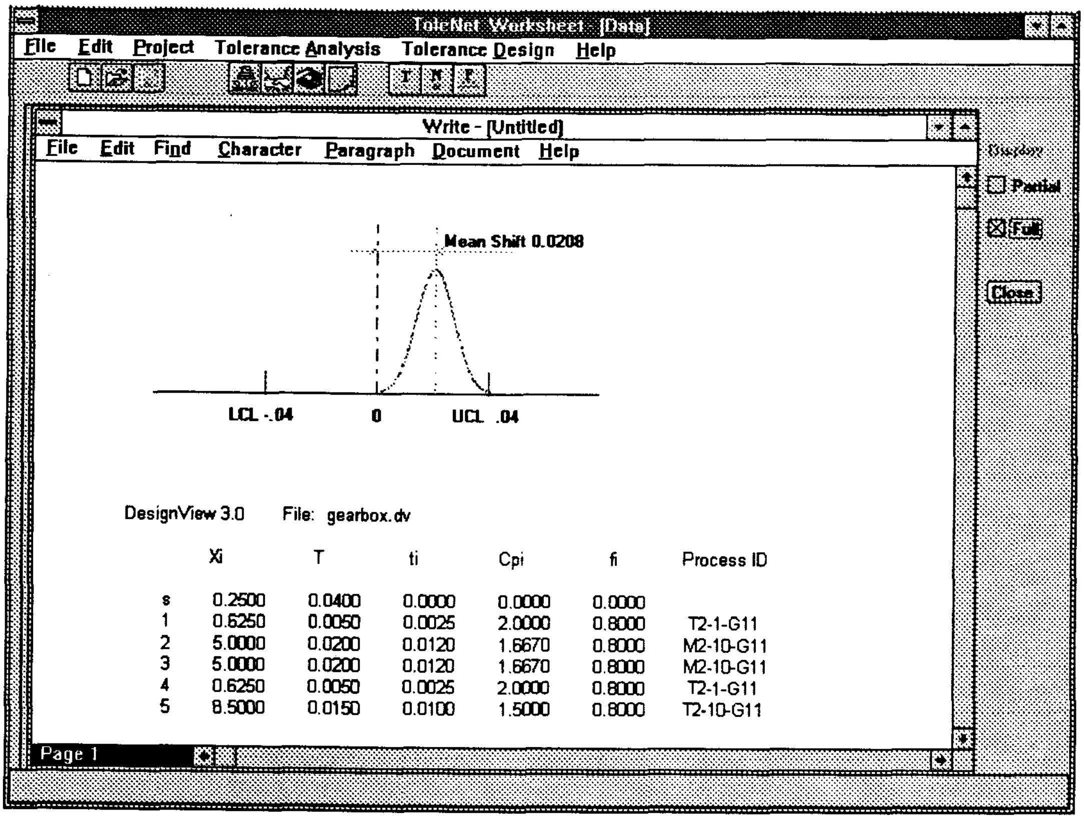


**Figure 8.1 Embedded MS Write and Report of Results**