Chapter 1
INTRODUCTION

In this chapter, an introduction is given that explains the role of tolerance in any mechanical assembly and its influence on design and manufacturing engineering departments. Moreover, various sources of variations that causes the difference in the dimensions of the component, and importance of tolerance allocation has also described in detail.

1.1 INTRODUCTION TO TOLERANCING

Manufacturing of parts with exact dimensions is practically not possible owing to various physical limitations, such as variable cutting conditions, hardware precision, software accuracy, dexterity of operators, assembly methodologies and material properties. To account these deviations the designer would assign a tolerance or range of acceptable values to each dimension of the parts to facilitate smooth flow of manufacturing (Chase, 1988). If a part size and shape are not within the maximum and minimum limits defined by the part tolerances, the part is not acceptable. Hence tolerances became an important design issue in the process of product development. This demands a great deal of understanding, knowledge, experience and common sense.
The focus of manufacturing industry is more now on the tolerance analysis. As the quality and price are both important, the demand for better quality with lower costs has been expected from engineers. Hence specification of tolerance limits on each dimension, with economic considerations became the primary design constraint. However with the support of technology, such as utilization of CAD/CAM techniques and other engineering design and analysis software, this task is successfully accomplished.

In the product development, the role of tolerances varies from stage to stage, as the objectives of each stage may be different from the other (Hong, 2003). All these factors are to be taken into account while designing the tolerances. Figure 1.1 explains the factors to be taken into account while designing the tolerances at various stages of manufacturing. The design demands that the tolerances be reduced to zero. However the manufacturing processes demand tolerances. Hence the manufacturing capabilities, process of manufacture etc are studied thoroughly before taking a decision on tolerances.

Figure 1.1: Role of tolerances in product life cycle
1.2 TYPES OF TOLERANCES

Two types of tolerances are common on mechanical drawings i.e. plus/minus (±) tolerances and geometric tolerances (Bryan, 1995). Plus/minus tolerances relate to linear distances or displacements and are stated in linear units (inches, millimeters, etc.) or they relate to polar displacements and are stated in angular units (degrees, radians, etc.). Linear tolerances are associated with linear dimensions, and angular tolerances are associated with angular dimensions. Typically, tolerances are stated in the same units as the dimension; hence a linear metric dimension has a linear metric tolerance.

1.2.1 Local Plus/Minus Tolerances

Manufacturing the products with exact dimensions is very difficult and uneconomical. Hence the measurements are displayed with a plus or minus (+/-) tolerances. This indicates that some margin of error can be allowed in manufacturing. However the designer must be careful to fix these tolerances, especially when deciding tolerances for mating parts, failing which results in a loose fit or may not fit at all.

1.2.2 Geometric Dimensioning and Tolerancing

The amount of variation allowed on size, orientation, location and form of a component is symbolically represented by Geometrical Dimensioning and Tolerancing (GD &T) (ASME Y14.5M-1994). More importantly, GD&T precisely defines the relationship between features
on a part and for identification of primary features that determine the
dependency among each other. Geometric tolerances are specified on
feature control frames and are primarily associated with features
located by basic dimensions.

It should be noted that only linear units may be specified in
feature control frame. For example, the geometric tolerances used to
control and specify angular tolerance zones using linear units, such
as inches or millimeters, unlike ± tolerances used to control angles,
which use polar units, such as degrees.

GD&T is the only method for precisely defining part geometry.
The geometric characteristic symbols used in feature control frames
are exhibited in Figure 1.2.

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<thead>
<tr>
<th>GEOMETRIC TOLERANCE AND DIMENSIONS</th>
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<tbody>
<tr>
<td><strong>Form Tolerances</strong></td>
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<td>Straightness</td>
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<td><strong>Location Tolerances</strong></td>
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<td><strong>Run out Tolerances</strong></td>
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Figure 1.2: GD&T Symbology
1.3 INTERNATIONAL TOLERANCE GRADES

In the process of designing a mechanical component, a system of standardized tolerances called International Tolerance grades (Paul, 1999) is often used. There are 20 International Tolerance grades and are represented as IT01, IT0, IT1, IT2, ........, IT17, IT18. These grades of accuracy are implemented by ISO, to cater to the quality demands of various branches of production. Table 1.1 and 1.2 summarizes the practical usage of International Tolerance (IT) grades and relation of machining processes to tolerance grades, respectively.

Table 1.1: Practical usage of International tolerance grades

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Table 1.2: Relation of machining processes to tolerance grades
1.4 SOURCES OF VARIATION

The following subsections describe certain sources of variations (Bryan, 1995) which influence the final product functionality in assemblies.

1.4.1 Manufacturing Process Limitations (Process Capability)

Manufacturing processes have a limit to their accuracy and precision. For any given process, certain tolerances are easily achievable without extra effort or care. These are well within the process capability and closer tolerances are achievable. But at other processes, it requires an increased cost due to the extra time and labor required or because some parts are out of tolerances and thrown away. Even closer tolerances may be virtually unachievable, due to the
inherent variation in the process. If a particular process is not accurate or precise enough, a different process or design should be sought.

### 1.4.2 Tool Wear

Cutting tools, drills, dies, all wear as they age, due to friction with the work piece (part). As tools wear they reduce in size and become dull. For example, this may cause the tool to cut a smaller hole, an out-of-round hole, or shear a surface farther from its nominal location.

### 1.4.3 Operator Error and Operator Bias

Operator error includes aspects such as improper handling of raw materials, improper clamping of material, and improper sequence of operations, among others. In automated processes, these errors are also possible, but hopefully with less frequency and effect. Factors such as training, turnover of personnel, time of day, all may have an impact on the frequency and severity of operator error.

Operator bias includes the effects of human factors and ergonomics, such as whether the operator is left handed or right handed, taller or shorter, stronger or weaker, etc. Depending on the process, these factors play a role in biasing the process one way or the other.
1.4.4 Variations in Material

Variations in the material from the foundry, or material formed or cut by a previous process contribute to possible variation. Of primary concern in mechanical Tolerance Analysis is the variation in size or form of raw material or stock shapes, such as sheet thickness, stock size variations or the angle between the sides of an extruded structural shape. Other types of material variation may include aspects such as hardness, ductility, porosity, chemical composition, or resistivity (or conductivity) to name a few.

1.4.5 Ambient Conditions

Ambient conditions such as temperature, humidity, vibration, cleanliness, and other also have significant contribution on the finished product. For example, if the machine is not operated in the specified temperature range, it can affect the lubrication process by either increasing or decreasing the viscosity of the lubricant.

1.4.6 Difference in Processing Equipment

Parts manufactured on a piece of equipment in one plant, such as vertical gun drilling machine, may be manufactured on a completely different machine at another plant, such as a horizontal gun drilling machine. Obviously there are different factors such as gravity and the capabilities of the machinery to consider in these cases. There may also be differences between the qualities of parts
manufactured on the same model of equipment in the same plant, due to number of factors.

**1.4.7 Difference in Process**

A part that is manufactured using different processes on different processing lines is likely to have different tolerances. Each process and machine will affect that part and its tolerances in a different way. For example, if a hole is die cast in plant A, drilled in plant B, drilled using a drill bushing in plant C, and reamed in plant D, the hole will have different tolerances as a result of each operation.

**1.4.8 Poor Maintenance**

Processing machinery may be neglected, and preventive maintenance may be lacking. In such cases, the precision and accuracy levels expected from the new machine and the poorly maintained machine may be different. Often this is a result of the demand and pressures of productivity, which may leave little downtime for maintenance.

Remember, the more difficult it is to service a piece of equipment, the less likely it will be serviced.

**1.4.9 Inspection Process Variation and Shortcuts**

Although this may not seem like a source of manufacturing process variation, it is perhaps one of the most likely sources of apparent variation between processes.
Consider a part that is manufactured in two shifts in a plant and inspected using different inspection process for each shift. Each inspection process uses different methods to “verify” that the tolerances have been met. Yet, each process reports different results for the same measurement. The apparent measured difference between the parts manufactured during day shift and night shift doesn’t exist. The error is in the shortcuts taken in the inspection process, not in the manufacturing process. A measurement can not be any more precise than the device used to make the measurement. As a general rule, the precision and accuracy of all measuring devices and procedures should be tested and verified before making any measurements. The error inherent in the inspection process must be quantified.

The various sources of inspection process variation for more information, included in Tolerance Stack ups. However, there is one inspection process variable that must be included in Tolerance Stack ups where it may be a factor: datum feature shift.

1.4.10 Assembly Process Variation

The assembly process can have a profound effect on assembly variation. Hence the designer must be thorough with the process of assembly. Assuming wrong assembly process during design can lead to serious problems. Moreover, the sequence of assembly operations have also a huge effect on the relationship between the features of assembled parts. For example, how parts are held, how and whether
they are fixture, which fasteners are started first, whether all fasteners are started before tightening any fasteners are the factors that affect stack ups conditions of the assembly. It is critical that the tolerance analyst must understand the assembly process and builds the tolerance stack-up accordingly.

Assembly shift is often the largest contributor in tolerance stack ups where parts are assembled and located by fasteners passing through holes in mating parts. Assembly shift must be included in all tolerance stack ups where parts are located by internal features within external features, such as by fastener passing through clearance holes or a key within a keyway in mating parts. The clearance between the mating external features and the internal features allows the parts to shift during the assembly process, hence the name assembly shift.

There are many other sources of variation not listed here. This is merely a sample of some of the sources of variation that are commonly encountered in industry.

1.5 DIMENSION CHAINS

Every assembly consists of different parts having different dimensions. Each dimension can be treated as an element and the sequence of elements forming the assembly is defined by a Dimensional chain. It is also referred to as dimension loop or tolerance chain.
A dimension chain can take the following forms (Bjorke, 1989) and are shown in Figure 1.3.

1. Elementary chain in which one end point is met only once.

2. Simple chain in which each dimension is used only once.

3. All other cases are categorized as interrelated chains.

\[ Y = f(X_1, X_2, X_3, X_4, X_5) \]
\[ Y_1 = f(X_1, X_2, X_5) \]
\[ Y_2 = f(X_3, X_4, X_5) \]

Figure 1.3: (a) Elementary chain (b) Simple chain (c) Interrelated chain.

1.6 IMPORTANCE OF TOLERANCE ALLOCATION

Determination of tolerances to the components of an assembly and the final assembly can be done in two ways. If the tolerances of all the components are known, then we can fix the functional tolerance of the assembly. This concept is known as tolerance analysis. If the tolerances of components are to be determined using the known functional tolerance of final assembly, then it is called Tolerance
allocation. Figure 1.4 clearly shows the difference between the
tolerance analysis and tolerance allocation.

![Figure 1.4: Tolerance Analysis Vs. Tolerance Allocation](image)

Tolerances for assembly can be decided based on the end user
requirements or its functionality. However the tolerances of
components must be worked out, keeping in view, the production
related constraints such as production processes, abilities of
workforce etc. The allocation of tolerances among various components
of assembly is a critical design issue as it requires the known
assembly tolerance is to be distributed to different components of that
assembly (Chase, 1990).

### 1.7 TOLERANCE VS Cost

The cost of manufacturing a component and tolerance are
inversely related. This relation is shown in the Figure 1.5. If the range
of tolerances is increased then the costs go down and vice versa. All
the available processes of manufacture are to be explored to minimize
the production cost. The process which has minimum production cost
and that can accommodate the required tolerances may be selected after a detailed comparative study.

![Figure 1.5: Tolerance Vs Cost relation](image)

Compact tolerance leads to high quality and high cost of product, whereas stretched tolerance leads to poor quality and low cost of the product. Hence it is the responsibility of designers to draw a compromise between the cost and quality in allocating suitable tolerances.

**1.8 SUMMARY**

This chapter provides with the necessity of tolerance allocation in a mechanical assembly. Moreover, the affect of tolerance on the design and manufacturing of a component has been critically examined. After thoroughly discussing the tolerance accumulation problem, importance of tolerance allocation has been explained. Finally, it provides the relationship between tolerance and cost of the mechanical assembly.