Chapter 2
Product Design

Abstract Product specification is a task in which most management disciplines, as well as engineering, take part. It is an innovative task and depends on the creativity of both management and the product designer.

The product designer's task is to develop a design to meet product specifications. It is up to engineering alone to make design decisions. However, during the design process, several decisions will arise that will affect the cost of the product. Such decisions should be made with the approval of management.

Several such decisions are presented in this chapter.

1 Introduction

Product specification, as well as product design, are innovative tasks and require creativity on the part of both management and the product designer. Several product specification methods are used by management for new products or improving the design of existing products.

A product has to seduce the customer with its options, appearance and cost. To arrive at such product specifications, almost all management disciplines, including manufacturing, should be involved.

There are several methods to assist management in coming up with ideas. These include:

- Conceiving ideas that would help make our everyday lives easier by fulfilling the needs of a specific task; this can lead to a new product or the improvement of an existing one
- Imaginative thinking; brainstorming
- Research and observation of the world and everyday life to inspire ideas about unfulfilled needs and to come up with product design ideas to fill those needs
- Basic research on market and consumer trends
- Observation of competitors; use of corporate spies, trade shows, and other methods may also be used to get an insight into new product lines or product features
- Creation of focus groups, employees, salespeople

Numerous ideas can be generated, and management has to evaluate and decide which ones deserve development, eliminating unsound concepts prior to devoting resources to them. To arrive at a sound decision, the following questions need to be asked:

G. Halevi, *Industrial Management—Control and Profit,* Lecture Notes in Management and Industrial Engineering, DOI 10.1007/978-3-319-03470-6_2,

- Will a customer benefit from the product?
- What is the size and growth forecasts of the market?
- What price range is anticipated?
- What is the current or expected competitive pressure for the product idea?
- What industry sales and market trends is the product idea based on?
- Is it technically feasible to manufacture the product?
- Will the product be profitable when manufactured and delivered to the customer?
- What features must be incorporated into the final product?

The remaining ideas are further analyzed for their potential business value. Management, i. e., marketing, sales, finance, etc., with the counseling and including the manufacturing, decides on the one product to develop and prepares product specifications of the main and secondary objectives and its features. Examples of the latter (values and priorities) may be specifically defined as follows:

- Ease of operation
- Durability (product lifetime)
- Reliability (low maintenance)
- Efficiency (low operating cost)
- Safety
- Ease of maintenance
- Noise level
- Weight
- Floor space occupied
- Aesthetics
- Cost
- Ease of installation
- Ease of storage

Etc.

The features as defined are a compromise of the conflicting interests of the various disciplines, and the definitions are of a business nature and not of engineering. Management will instruct manufacturing to produce the product as specified.

1.1 Manufacturing—Product Specifications

The designer's work must always be directed toward a goal. This goal is usually stated in general non-engineering terms without any implication as to the means to be adopted to achieve it.

Product design specification is a statement of what a product is intended to do. Its aim is to ensure that the subsequent design and development of a product meets the needs of the user. Product design specification acts as an initial boundary in the development of a product. The product specifications that instruct manufacturing are of two natures: qualitative and quantitative. The distinction can be seen as the difference between "What does the product do?" and "How will the product do it?"

Product specification indicates what is required but not specification of the product itself. Describing the actual product is done through the technical specifications once the product has been designed. The difference is important, since describing the product itself at the stage of creating a product design specification would effectively constrain the range of alternatives considered during the design process.

It is important that the designer does not rush into solving the problem as stated in the goal. The purpose of the task must first be understood, and then must be converted into a set of quantitative engineering specifications. For example, if the goal is to design a conveyor belt, it should be realized that the purpose of the endeavor is to move items from one place to another. The conveyor belt is only one possible solution. Another possibility to be considered is rearrangement of the shop-floor layout in order to eliminate the need to move items. The goal in designing an air-conditioning unit is to create comfortable conditions of temperature and humidity. If the problem is initially stated in broad, general terms, more possible solutions will be considered, thus enabling better solutions to be found.

The second stage is to transform the general terms used in the task specifications into values. This will be done by collecting information and by computations. The term “comfortable conditions” used in the air conditioning example must be converted into a statement of the form “room temperature of 22 °C and relative humidity of 50 %.” Such factors as room size, the normal temperature in the area, time required to reach the desired conditions, the wall sizes and locations, and the number of people in the room must be specified. In addition, the amount of heat transfer and the air flow must be computed in order to reach the proper engineering task specification. The engineering task specification does not worry about air-conditioning; it concerns itself with specified values.

The secondary objectives of design include many requirements, several of which are contraindicative to one another. ***Management and design*** should discuss this problem with one another in order to come up with an agreeable and efficient compromise. Some of these requirements are:

Ease of operation:

- Durability—product lifetime
- Reliability—low maintenance
- Efficiency—low operating cost
- Safety
- Ease of maintenance
- Noise level
- Cost
- Aesthetics
- Ease of installation
- Ease of storage
- Ease of transportation
- Compatibility with its environment

Ease of production:

- Size
- Weight
- Volume
- Mechanical strength
- Ease of assembly
- Product design specification
- Floor space
- Recycling
- Ease of maintenance, etc.
- Ease of operation
- Durability, long service life
- Reliability, low maintenance cost and short down time
- Efficiency, low operation cost
- Volume, plan area, front area
- Use of available resources
- Use of standard parts and methods
- Reduction of rejects, scrap parts and material
- Design for distribution

1.1.1 Management Control

Design should utilize the two groups of ease of operation and ease of production as check lists so that management can be certain all points have been covered.

1.2 Manufacturing—Product Design

Product design's primary function is to conceive a product that meets management's product specifications. Management specifications are set through discussion groups involving all management disciplines, including manufacturing. There exists the possibility of bias due to the power of a specific management group's interest or through the persuasive powers of a specific member. Regardless, management has the final decision as to what the product should be and what it should look like.

Engineering's task is to prepare drawings for product assembly, product structure, subassemblies and items, and, finally, process planning. The drawings are the obligatory document for driving the phases of production. Some control must be exercised over these stages. The process planner is bound by the defined drawing and, therefore, should work with engineering in an *interactive manner*.

The designer is a problem solver who, given a problem (in this case, a need), applies such fields as physics, mathematics, hydraulics, pneumatics, electronics, metallurgy, strength of materials, dynamics, magnetism and acoustics in order to find a solution, namely, the new product. His/her main responsibility is to design a product that meets the customer specifications. A parallel target is to design a high quality, low cost product.

There is no single solution to a design problem, but rather a variety of possible solutions surrounding a broad optimum. The solution can come from different fields of engineering and apply different concepts. The designer is bound by constraints that arise from physical laws, the limits of available resources, the time factor, company procedures, and government regulations. Among all these possible solutions, the designer, in consultation with the process planner, selects the one that seems most suitable.

Product designers are not process planners. However, whatever ideas they develop during the design stage will significantly affect the manufacturing process and the process planning. They do not go into the details of the manufacturing process, but usually work by intuition. However, parts that were designed with a specific manufacturing process in mind might turn out to be very difficult to manufacture if the process has to be changed. In such cases, it should be remembered that parts are designed subject to functional, strength or manufacturing constraints. The drawing of a part should always be seen as a constraint by the process planner; it might be an ***artificial constraint*** if the manufacturing process is the controlling factor in part design.

Studies have indicated that the incurred cost of the engineering stages, i. e., product design, detail design, testing and process planning, is about 15 % of the product cost, while the production stage accounts for 85 %. However, since the committed cost of the product is about 90 % established in the engineering stages, it is worthwhile not to rush but rather to extend the thinking time in design before making decisions.

The product designer should bear in mind the manufacturing process that will produce the designed part. Each manufacturing process has its advantages, capabilities and limitations. The cost of a part can be kept to a minimum if its features, dimensions and tolerances match the capabilities of one of the available processes. Otherwise, the cost might be excessively high or the production might even be impossible. Designers do not define the process plan, but rather steer toward utilization of existing processes, preferably to one available in their own plant.

The quality and reliability of the designed product are determined and controlled by the designer.

Quality is a measure of how closely the product conforms to the secondary objectives set by management and the compromise made among these conflicting objectives.

Reliability is defined as the probability that the product will perform a required function under given environmental conditions for a specific period of time. Reliability is measured mainly in terms of failure rate.

Management should make sure that the designer has considered at least three possible design solutions, and that they were discussed with the process planner before establishing the final design.

1.2.1 Product Material Selection

Choosing the right material for a product can be critical to the success of that product. In some cases, the decision as to what material to use is obvious, but in others it may need some creative thinking and computation.

Material selection is part of the process of product design. The main objective of material selection is to minimize cost while meeting product performance objectives.

Materials are an important concern for any manufactured product. Choosing the right material for the right product is as important as any of the main criteria that would normally be involved in bringing a product to market. The selection can influence design on many levels. Perhaps the most obvious considerations are manufacturing costs and performance of the end product. A balance needs to be sought between costs, manufacturing feasibility and finding the right material for the job.

Clearly, different materials have different properties:

- Metals are easy to form, from liquid, by solid deformation, or by metal removal
- Ceramics are particularly heat resistant and hard
- Plastics can be easily formed into an infinite range of shapes and colors
- Glass is hard and has some outstanding optical qualities
- Wood is easy to work without necessarily using expensive machinery and is also naturally highly decorative

It is easy to consider materials purely from the perspective of their obvious functional attributes—for example, the hardness of ceramics versus metals or the formability of plastics over wood—but the emotional and visual qualities of materials help define the product as much as the form and function. The surface texture, the translucency, the sponginess or hardness, all have an effect on the way a product is perceived and used. A specific quality may well be the starting point for an idea: 'We need a packaging that has a seductive quality', or 'We need something aggressively modern'.

Evaluating the requirements for the final product should help in deciding the right material. Mobile phones, for example, need to be produced in high volume, they need to be made from a fairly rigid but resilient material, and they need to be formed into a variety of complex, sometimes highly detailed shapes.

1.2.2 Management Control

Of course, cost per kg is not the only important factor in material selection. An important concept is 'cost per unit of function'. For example, if the key design objective was the stiffness of a plate of the material, then the designer would need a material with the optimal combination of density, Young's modulus and price. Optimizing complex combinations of technical and price properties is a difficult process to achieve. Adding to the complexity is the fact that the designer has the option of arriving at the same product stiffness and strength with several materials through different configurations of the part. The strength is a function of the part's cross-section. One may select a material of extra strength and cost by reducing the weight of the part (cross-section), or by increasing the part's cross-section and weight.

Management should follow the designer's material selection carefully and critically.

1.2.3 Standard and Purchase Items

The product designer is responsible for meeting management's product specifications. They use their expertise and creativity and no one should interfere in their engineering decisions, unless those decisions are managerial or economic in nature.

In design, there are decisions that are mandatory for meeting the product specifications and there are fillers. For example: assume a need for a shaft with bearings at the two ends. The length of the shaft and the bearing type are mandatory to the product. But a bearing needs housing, and housing needs something to support it. These are essential to the design but are also ***"fillers"***, meaning they are not essential to the product's performance. No designer would even think of designing a ball bearing, because it is a ***standard item***, produced by a specific factory whose business is bearings. It should be bought. The housing support is "filler" in the sense that its design usually does not contribute to the product's performance. It is also possible that there are some standard items that might do the job at a lower cost, or that they could just set a simple plate to hold the bearing.

1.2.4 Management Control

Management should oversee the design from an economic perspective and encourage the designer to check the benefits of using standard items and simple "filler" designs as much as possible.

1.2.5 Safety Factor

To avoid failure, the designer must apply mathematical procedures. A good designer will distinguish between the mode of failure and the failure mechanism. To do so, the following procedure will most likely be applied:

- Determine the mode of failure
- Define the failure mechanism
- Select a theory of the failure
- Setup a mathematical model to determine the relationship between the variables
- Solve the mathematical expression and assign dimensions

Simple assumptions, for example, that the materials are homogeneous and ductile, must be made in order to construct the mathematical model describing the physical situation and predicting the behavior of the element being designed. The designer must be aware of these assumptions and decide if they are applicable in the particular case.

Potential errors in design can result from the following scenarios:

- The designer fails to foresee all possible modes of failure
- The designer foresees the mode of failure, but is unable to select and set up a mathematical model

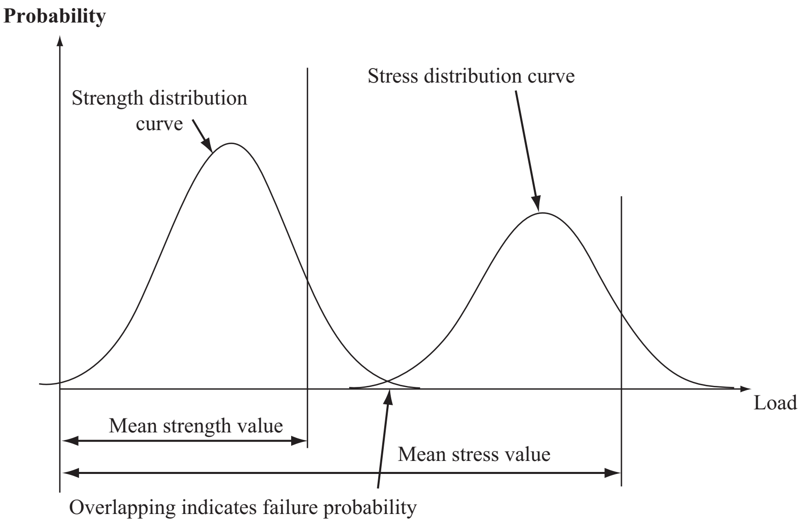


Fig. 2.1 The relationship between the distribution of strength and stress

- The designer is successful in the above steps, but has made a mistake in the calculations or in the manipulation of the model
- The designer is willing to accept a small risk

To ensure against failure, the designer must provide a margin of safety - the ***"safety factor"***. The safety factor is determined as a ratio of the design strength to the applied load and is always greater than 1. Tables for factors of safety are given in all engineering handbooks. For mechanical items, it is customary to use a factor from 4 to 40. In this method, the designer assesses the global situation and decides on the magnitude accordingly. Another approach to the selection of the safety factor is illustrated in Fig. 2.1.

Both the load capacity (strength) and the actual load (stress) are not fixed values, but, due to the nature of the design, have a certain distribution around a mean value. The specific shape of the distribution curve depends on the particular problem. The safety factor is defined as the ratio of the mean load capacity to the actual load. The overlapping area of the distribution curves indicates the probability of failure. The designer *can choose any desired reliability value* by using statistical theory to compute the corresponding safety factor.

The master product design method exists so that the designer can check and be reminded that the reliability of the product is a design parameter, and to assure that the designed probability of failure is a conscious decision and not the product of negligence.

1.2.6 Management Control

The decision as to the value of the reliability factor cannot be made by the designer alone, and must be communicated to and approved by management. This decision affects the cost, weight, and processing time of the product, as well as the product's performance. Above all, it minimizes the possibility of failure and breakdown of the product.

In case of failure, it may be automatically determined if the failure could have been predicted by the designer. If not, re-evaluation of any of the following may indicate where the error lies: mode of failure; the failure mechanism; the theory of failure; the mathematical model; the solution of the mathematical expression and assigned dimensions; the data used for the dispersion of the load, the actual load, and the method used for the applied load (Fig. 2.1). A software algorithm will be initiated and a recommendation for action can be reached automatically.

1.2.7 Tolerances

Potential errors in manufacturing can either affect production performance, product life, and product assembly or have no significant effect on the product at all. In manufacturing, it is impossible to make each dimension and characteristic agree exactly with one specific value. Every element will deviate from the theoretical value. In many cases, even a gross deviation from the component geometry and characteristic can exist with no significant effect on product performance. On the other hand, in some cases, a microscopic deviation can have a catastrophic effect.

To ensure against failure, the designer specifies the permissible deviations, that is, the acceptable range of values. In other words, the designer specifies a tolerance.

In mechanical parts, there are three types of dimensional characteristics which need to be controlled by tolerances: Size, Shape and Location. There are three classes of fit between mating parts, e.g., shaft and holes:

1. Loose fit. Used for dynamic fit.
2. Neutral fit. Used for static fit with no load.
3. Tight fit. Used for static-fit loaded parts.

There are two methods of applying the tolerance:

1. Basic hole system.
2. Basic shaft system.

Which system is adapted depends on the method of processing and the state of the raw materials prior to processing. In making a tolerance choice, the designer will usually refer to standard systems of tolerance and charts that are well represented in the literature.

Tolerances are applied not only to diametric dimensions, but also to longitudinal dimensions and assemblies. The calculation of tolerances is always based on "allowances", that is, the allowed difference in dimensions between the mating items.

The designer may specify and divide this allowance in any way he/she chooses, as long as the total allowance is secured.

The following example demonstrates the “risk” that the designer is willing to take in assigning tolerances. For example, the assembly of five items in a row may have an allowance of 0.25 mm. In order to assign a tolerance to each component, an even *arithmetic distribution* can be used and each component assigned a tolerance of

$$T = 0.25 / 5 = \mathbf{0.05mm}.$$

If the items are processed individually, and each one deviates along the full range of the tolerance, ***statistically*** controlled conditions prevail. In such cases, statistical tolerance can be used. The principle involved is that statistical deviation of an assembly is equal to the square root of the sum of the squares of the standard deviations of the dimensional involved. In the tolerance field, this principle is expressed as follows: *The assembly tolerance is equal to the square root of the sum of the squares of the item tolerances*. Thus, in the example considered above, the assembly tolerance, which consists of five items with allowance of 0.25 mm in even distribution in each item of tolerance (T), will be as follows:

$$0.25 = (5 * T^2)^{1/2} \quad T = .25 / 5^{1/2} \quad T = \mathbf{0.11mm.}$$

This is a considerable difference from the item tolerance of 0.05 mm obtained with arithmetic distribution.

1.2.8 Management Control

The personality of the product planner should be one of skill, intuition, imagination and creativity. This position is usually held by an experienced engineer. After forming the concept and main subassemblies and items for functionality and strength of the product, the product designer’s next task is to transfer these ideas, i. e., to prepare assembly and detail drawings. This task is an editing process, constrained by the explicit rules and grammar of engineering language, namely, drawings. The decisions required at this stage are concerned with layout, and the noncritical dimensions. The personnel for this stage are young engineers or draftsmen. They also usually prescribe the tolerances. They may not always know the designer’s intentions, but they control the tolerances and the dimensioning method.

Tight tolerances afford the designer peace of mind and security; however, they also raise the cost of processing, the processing time, and the utilization of resources. This often becomes an area of internal conflict between manufacturing themselves, i. e., between the designer and process planner, as well as external conflict with the shop floor.

In the metal cutting process, there is a direct relationship between tolerance and maximum depth of cut. A low tolerance calls for a small depth of cut for the final cut and a low feed rate, which increase the processing time. Furthermore, a low

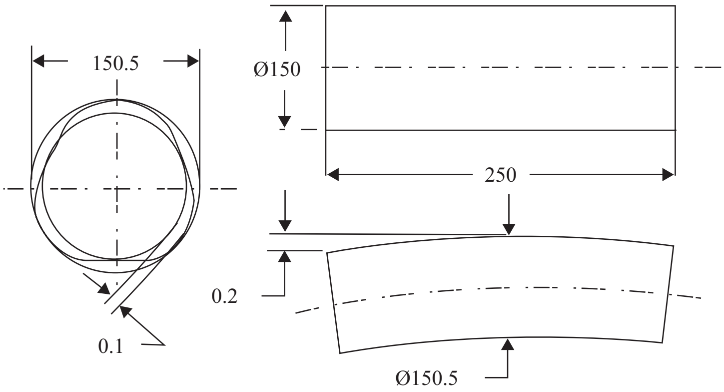


Fig. 2.2 Possible good part that meets diameter tolerance

depth of cut calls for added cutting passes, which further increase processing time of the item.

In many cases, the processing time for the required tolerance and the specified tolerance might be increased by ten times.

Therefore, management should be involved in order to make sure that reasonable tolerances are specified. The product planner should, thus, be kind enough to check the drawings carefully before approving them.

1.2.9 Geometric Tolerances and Surface Roughness (Integrity)

All bodies are three dimensional, and, in an engineering drawing, a body is assumed to be placed in a system of three perfect smooth planes oriented exactly 90° to each other. However, perfect planes cannot be produced. The shape tolerances cannot guarantee that the part produced will meet the designer's intentions.

For example: At the top of Fig. 2.2, a drawing of a straight shaft diameter of Ø150 ± 0.5 is shown. At the bottom of the figure, the produced part is shown. The produced part meets the specified tolerance. At any cross section of the part along its length, the diameter will be Ø150 ± 0.5; however, the center line is not a straight line but a curve. No indication on the drawing prevents such a curve. Furthermore, the shape must not be a perfect circle, as can be seen in Fig. 2.2. The circularity of the part must be within two circles, one of Ø150 and the other Ø150.5.

Another example is shown in Fig. 2.3. The drawing on the left shows the designer's intentions, and on the right the produced part that meets the drawing specifications. The drawing does not specify that the two cylinders must be concentric.

Geometric tolerances come to enable the designer to specify their intentions more precisely. There are several geometrical tolerances specifying form and positions,

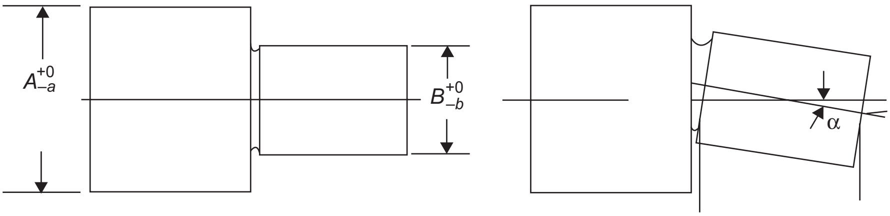


Fig. 2.3 Part that meets drawing specifications

such as: flatness, straightness, perpendicularity, concentricity, etc. These are defined in the *ISO Standard for Tolerances of Form and Positions*.

Surface roughness (integrity) While the preceding standards are related to macro-geometric properties, it is also important to define the micro-geometric characteristics of mechanical surfaces, which can have a functional significance as important as that of macro-geometric tolerances. The *ISO Standard Surface Roughness* gives basic definitions of roughness criteria and definition of surfaces of reference, as well as the symbols to be used in drawings, e.g., 3.2 µm R_a to characterize the arithmetic mean roughness taken relative to the center line reference. There are more than 50 different parameters available that describe surface conditions. Actually, most manufacturers use combinations of no more than two to four parameters for accurate surface-finish measurement. Listed here are some of the surface-finish parameters used in the industry today.

R_a Arithmetic averages roughness

Roughness averages are the most commonly used parameters because they provide a simple value for accepting/rejecting decisions. Arithmetic average roughness, R_a (also designated AA or CLA), is the arithmetic average height of roughness-component irregularities from the mean line, measured within the sampling length, L.

R_q—RMS—Geometric averages roughness

Geometric averages roughness R_q, or root mean square (RMS) is more sensitive to occasional highs and lows, making it a valuable complement to R_a. R_q is the geometric average height of roughness-component irregularities from the mean line measurement within the sampling length.

1.2.10 Management Control

Geometric tolerances and surface roughness (integrity) might be required for aesthetic purposes but usually increase processing time and limits, and constrain both resource utilization and jigs and fixtures required.

Management should be active in making a decision as to which definition standard to use, and to make sure that the tolerance values will not be overstated. Many designers put aesthetics over cost, and they must be controlled.

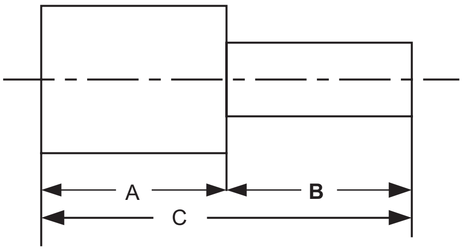


Fig. 2.4 A redundant dimension can be the cause of out-of-tolerance parts

1.2.11 Dimensioning and Datum

The design decisions reached in the engineering design stage are transferred to the process planning stage and other manufacturing stages in the form of technical drawings. The technical drawings act as the input to process planning. They include complete information on the geometry and associated data, such as: geometric shape of the parts, dimensions, tolerances, geometric tolerances, surface finish, and the raw material. Each one of these data affects the process planning decisions.

An item should be defined in such a way that, when assembled with the whole mechanism, it will fulfil its technical functions and be of a dimension and tolerance so that it can be mounted in a subset of parts in a completely interchangeable manner. To dimension the items, which would be assembled with each other, the dimensioning should originate at a ***datum***. Datum is usually marked with a letter of the alphabet and placed in a box attached to the edge view of the surface. The drawing may, of course, contain any unimportant details which have nothing to do with functioning and assembly. The dimensions for these need not originate at a datum.

An example of *correct and incorrect dimensioning* is shown in Fig. 2.4. Considering the horizontal dimension of an item, it includes three dimensions: A, B, and C. A redundant occurs when all three dimensions are given as:

$$A = 50;\ B = 30;\ C = 80.$$

The arithmetic is correct, but, due to variations in processing (tolerances), the part cannot meet the defined tolerances, which might be, for example:

$$A = 50 \pm 0.1\,; B = 30 \pm 0.1\,; C = 80 \pm 0.1.$$

The difficulty can be corrected by omitting one of the dimensions. The two dimensions that should be retained depend on manufacturing convenience or the functional requirements of the part. From the discussion above, it is obvious that only sufficient dimensions should be placed on a drawing. Any additional dimensions will nearly always result in items that meet the drawing but outside of the specified tolerances.

To meet the functions of an item, and due to machine inaccuracies, any dimension on a drawing must be accompanied by tolerances. The stack-up tolerances are a function of the dimensioning method assigned by the designer.

The basics of tolerance arithmetic are explained in the following examples:

Figure 2.5a shows a chain of four dimensions with their tolerances. One task is to define the length of the part overall. The nominal length will obviously be:

$$L = A + B + C + D.$$

The maximum length will be:

$$A + a + B + b + C + c + D + d = A + B + C + D + (a + b + c + d).$$

The minimum length will be:

$$A - a + B - b + C - c + D - d = A + B + C + D - (a + b + c + d).$$

And the tolerance will be:

$$l = a + b + c + d.$$

Figure 2.5b shows the total length with its tolerance (L±l), as well as the tolerance of dimensions A, B, D. The problem is to define the tolerance of C.

The nominal dimension of C is:

$$C = L - (A + B + D).$$

The maximum length will be:

$$C = L - (A + B + D) + (l + a + b + d).$$

The minimum length will be:

$$C = L - (A + B + D) - (l + a + b + d).$$

And the tolerance will be:

$$c = l + a + b + d.$$

The resultant dimension is, therefore:

$$C \pm c(l + a + b + d).$$

These results show that, whether the dimensions are added or subtracted, the resultant law of tolerance is as follows:

The interval tolerance of the result is equal to the sum of the tolerance of the components.

Figure 2.5c shows an example with the same four dimensions, except that A and E are not dimensioned individually, but their sum is B. If B is the tolerance as before, the tolerances of A and E have to be reduced (dimension A or E should be omitted). On the other hand, the tolerance of C will be reduced to $c = l + b + d$, assuming, of course, that the different tolerances are of the same magnitude as in the cases of 2.5a and b.

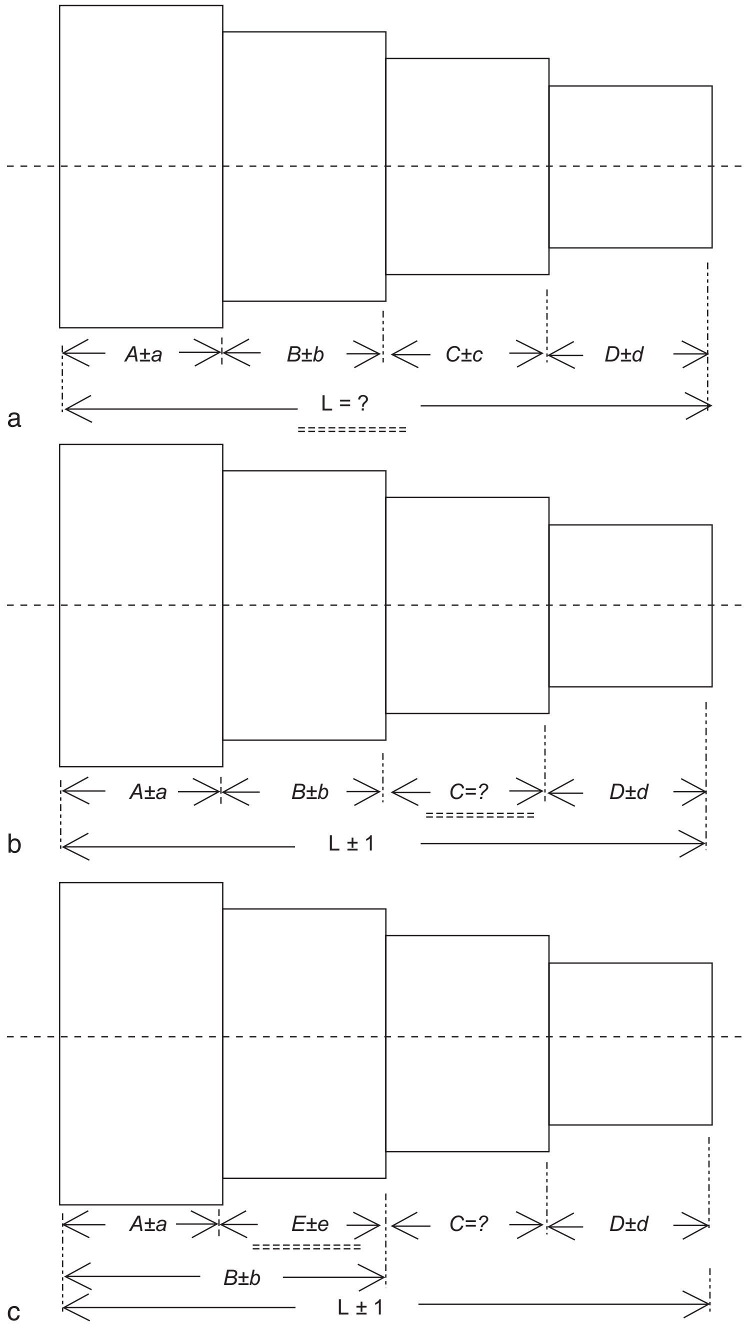


Fig. 2.5 Dimensioning method effect on tolerance stack-up

1.2.12 Management Control

The importance of correctly determining tolerance and setting in production cannot be over-emphasized. A process plan which cannot guarantee the manufacturing dimensions required by the design department would be meaningless for a manufacturing industry.

The use of correct methods of diminution in determining tolerance should be a great help to process planners. Management should enforce the interaction between the product designer and process planner.

1.3 Production Design and Process Planning

1.3.1 Accuracy Problem in Manufacturing

A detailed and comprehensive examination of an item drawing is not only a condition to producing the item so that it is functionally correct, but is also the best approach for finding a suitable process for manufacture and inspection of the desired item.

However, it is also important to emphasize that the technical drawing does not limit the freedom of the process planner when designing a suitable process plan. In fact, it is possible that, in certain circumstances, the process planner will suggest changes in the design, for example, a better tolerance method because of constraints in production. The process planner has plenty of freedom in designing the process plan, after first fulfilling all of the functional conditions defined by the product design.

The process planner's task is to translate the requirements expressed by the rich and powerful language (the drawing) into a machinery language (the machine, the fixture, the tool) with a much more limited vocabulary than the drawing. However, for various reasons related to the selected process plan, such as the mode of clamping the item onto its fixture and economic considerations, it very often happens that the functional dimensions are not executed directly in manufacturing. In this case, the functional dimensions are obtained as indirect dimensions, rather than direct dimensions, or, in other words, as resultant dimensions of a chain of direct dimensions. The tolerance of a resultant dimension is then the sum of the tolerances of the component dimensions which are given by the process used in manufacturing.

Obviously, the result of this is that the tolerance of the component dimensions has to be small enough for their sum to comply with the tolerance of the resultant dimension given on the drawing. This can raise problems of tolerance in production when production equipment is not able to produce items at the small tolerances required. In this case, the only solution is to increase the tolerance of the resultant dimension, which can contradict design requirements, or to change the process plan and to use more precise equipment, which means *increasing the cost of manufacturing*. This situation can be considered to be the fundamental accuracy problem in manufacturing.

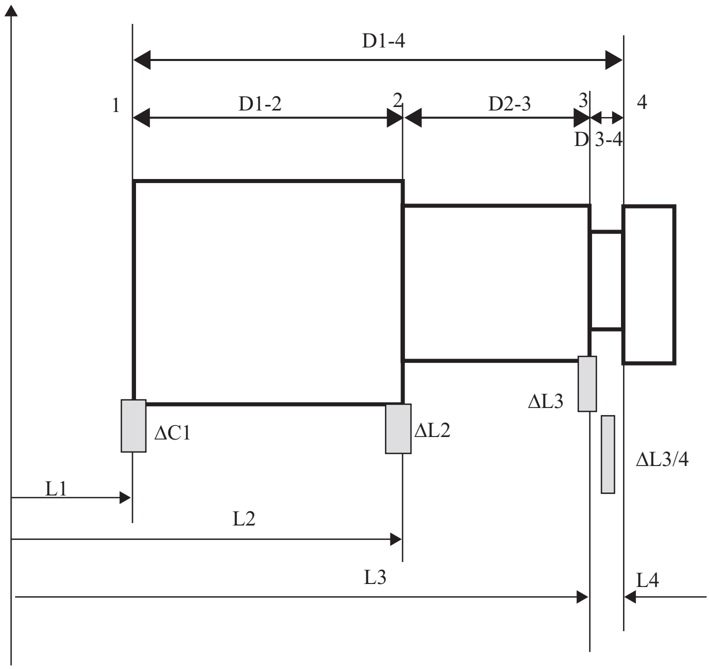


Fig. 2.6 Possible errors in meeting the longitudinal dimension

Before going into details of determining tolerance, it is useful to define the different types of dimensioning encountered in manufacturing:

- *Work piece drawing* – defined by the designer to assure correct functioning of the work piece
- *Machined or manufacturing drawing*—specified by the process planner to instruct the machine operator or NC programmer so as to assure that the work piece will conform to the drawing
- *Setting drawing*—defined by the process planner, defining the tools and fixture positioning in the machine system of reference

In part-drawing, there is a reference point to each dimension. However, in machining, a *different reference point* is used, that of the machine and the fixture reference point.

The process of transferring dimensions from the work piece drawing to the machining and setting drawing may result in stack-up tolerances and might create errors.

An example of determining the tolerance of an item is given in Fig. 2.6.

The D dimensions are the drawing dimensions, the L dimensions are the dimensions from the machine datum lines. The resultant dimensions are computed dimensions. The possible errors and deviation from the nominal are shown by shaded areas. For example, the ΔC1 error is due to an inaccuracy in placing the part on the machine depending on the type of positioning, by a plane contact or by punctual contact. ΔL errors are due to machine accuracy and repeatability. A ΔL3/4 error is due to tool dimension.

The possible accumulation of errors is taken into consideration in computing the chucking location and type, and in selection of a proper machine for the job. If a problem arises, re-evaluation of the parameters will be made and a permanent correction (learning feature for specific machine capability or system) or a temporary correction for a specific fixture will be made. The process will then be re-computed.

The importance of correctly determining tolerance and setting in production cannot be over-emphasized. A process plan which cannot guarantee the manufacturing dimensions required by the design department would be meaningless for a manufacturing industry.

The use of correct methods of diminution determination of tolerance should be a great help to process planners. Management should enforce the interaction between the product designer and process planner.

1.3.2 Management Control

From the previous derivations, we reach the following conclusions

- The machine accuracy is not established by the smallest item tolerance.
- The actual tolerance is not according to the designer's (drawing) tolerance but according to the machine and fixture accuracy and the sequence of operations.
- If no machine of the required accuracy is available, then management should interfere and call the product designer and the process planner to propose solutions. The manager will then select the best solution.

1.3.3 Production Variation and Failure Due to Processing

Failure of products due to processing may occur in the case of errors in defining the process plan or due to improper dimensioning of the design.

The quantities in manufacturing are of a stochastic nature because many errors/factors influence their values. The distribution of these values can be described by statistical laws such as normal law, which is applicable to many random distributions in manufacturing. The normal law can be represented by the curve shown in Fig. 2.7.

Figure 2.7 shows that 68 % of the values are in the range of $\pm\sigma$ and that 99.75 % are in the range of $\pm 3\sigma$ which is taken as the ***tolerance interval*** because it rejects only a percentage of 0.25 % of the parts when production is well-centered in the tolerance interval.

Statistically, dimensions are based and logically built around the phenomenon that variation in a product is ever-present. There is a natural variation inherent in any process due to wear of tools, material hardness, spindle clearance, jigs and

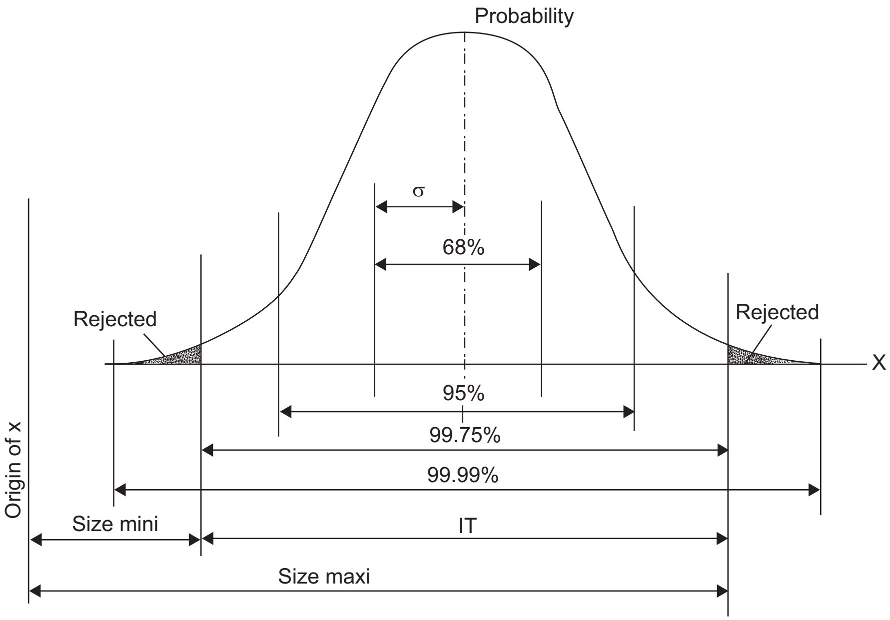


Fig. 2.7 Normal law and interval of tolerance IT

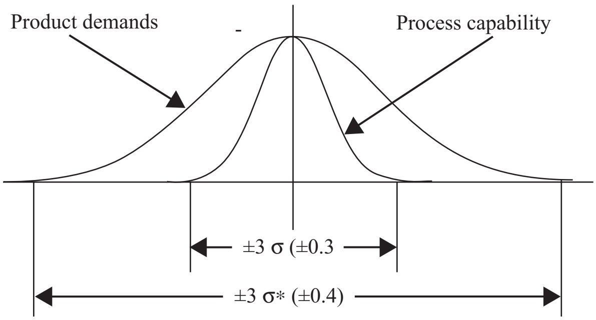
fixtures, clamping, machine resolution, repeatability, machine accuracy, tool holder accuracy, accumulation of tolerances, operator skill, etc.

Variation will exist within the processes. Parts that conform to specifications are acceptable; parts that do not conform are not acceptable. However, to control the process, reduce variation and ensure that the output continues to meet the expressed requirements, the cause of variation must be identified in the data or in the dispersion of the data. Collections of these data are characterized as mathematical models called "Distributions" that are used to predict overall performance. Certain factors may cause variation that cannot be adequately explained by the process distribution. Unless these factors, also called "assignable causes", are identified and removed, they will continue to affect the process in an unpredictable manner.

A process is said to be in statistical control when the only source variation is the natural process variation, and "assignable causes" have been removed. A control identifies changes between items being produced over a given period, and distinguishes between variations due to natural causes and assignable causes. Corrective action may, therefore, be applied before defective products are produced. Parts will be of the required quality because it is manufactured properly, not because it is inspected. In most cases, quality should not be left to chance. Sorting conforming parts from nonconforming ones to produce a yield is not usually the most cost effective method.

Variations that are outside of the desired process distribution can usually be corrected by someone directly connected with the process. For example, a machine set

Fig. 2.8 Product demands and process capabilities



improperly may produce defective parts. The responsibility for corrective or preventive action in this case will belong to the operator, who can adjust the machine to prevent recurring defects.

Natural variation will establish ***process capability***. Process capability is the measure of a process's performance. Capability refers to how capable a process is of producing an item that is well within engineering specifications.

The process capability is established at process planning. Actually, the process planner, through his/her decisions, establishes the suitability of the process to the task and the anticipated scrap and rework percentage. Inherent capability of the process factor (CP) will indicate if the process is capable, the process is capable but should be monitored, or the process is not capable.

The product-allowed variations (tolerances) are compared to the allowances of the process capabilities. Both are regarded as normal distributions around the mean value, as can be seen in Fig. 2.8.

The tolerance interval of product demands, as well as the process capability, is regarded as $\pm 3\sigma$ of their normal distribution. The 3σ span indicates that 99.73 % of all parts will be within the tolerance interval. For the example shown in Fig. 2.8, 99.73 % of the parts, regardless of the product demands, will be within ±0.3, while the required tolerance is ±0.4; this gap means that (according to normal distribution tables) 99.994 % of the parts will meet product demands. The bigger the difference between the process capability and the product demands, the greater the chance of reducing production of reject parts until it becomes easy to predict.

The trend today is to work with **6σ or even 9σ**, the result of which is that the chance of producing a reject part is 1 in 100 million. Which range to select is up to the process planner.

Figure 2.9 shows the case in which the product demands are lower than the process capability. This means that the process planner deliberately (probably due to the available resources) plans to have a certain percentage of reject items. If the inspection reveals the same percentage of rejects, it means that all is functioning correctly and nothing should be done. Natural process variation may only be corrected by redesigning the part and the process plan.

Successful control requires action in the form of a monitoring system. A control chart may be used to record the average fraction of defective parts at a work station.

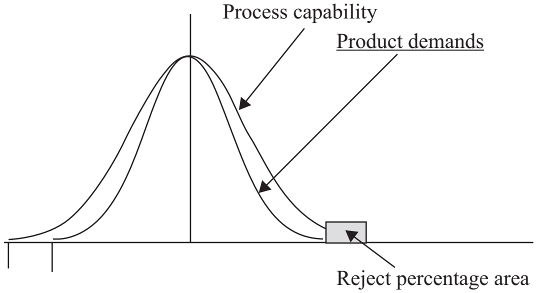


Fig. 2.9 Product demands and process capabilities

Through application of statistical techniques, problems are identified, quantified and solved at the source in an optimum time. Out-of-Control conditions become evident quickly, as does the magnitude of the problem. With this information, action can be taken before the condition becomes a crisis.

1.3.4 Management Control

Management should consult with the product designer and process planner, and make the decision as to what rate of reject is reasonable, i. e., decide which range of sigma (**3σ, 6σ, 9σ**) to adapt.

1.3.5 To Meet Geometric Tolerances

There are various causes of geometric inaccuracy. For instance, flatness, angularity and perpendicularity errors in milling can have one of several causes: machine tool geometric errors, work piece deflection, cutting tool deflection, tool eccentricity, tool flatness, and, in the case of producing the item in more than one subphase, refixturing of the item on separate surfaces.

Concentricity, run out and true position inaccuracies will occur when separate features are being machined on separate fixtures in more than one subphase. Each refixturing of the item introduces a large error. Machine tool errors, tool deflections and item deflections contribute to inaccuracies as well. In order to devise a process that meets geometric tolerance specifications, the following precautions should be observed:

- *Fixturing* When a geometric tolerance is specified, the only way to meet the specification is to machine the relevant surfaces in a single subphase, i. e., in one fixture.
- *Machine accuracy* Items can only be as accurate as the machine on which they are produced.
- *Tool accuracy*; similarly, items can only be as accurate as the tool used to produce them.

- *Tool deflection* Tools deflect under the load generated by the cutting forces, so these forces have to be controlled by appropriate cutting conditions.

There are many other factors, such as temperature influences, vibrations, material heterogeneities, kinematics, and so on. In spite of the accumulation of all these errors, it is possible to produce accurate items by careful choice of machine tools, machine conditions, appropriate tooling and accurate fixtures, and last but not least, an optimal choice of strategies for determining tolerance.

1.3.6 Management Control

Geometric tolerances greatly increase the processing cost of the product. Management should have control of such tolerances. They should supervise and instruct the product designer to be very frugal when assigning such tolerances.

http://www.springer.com/978-3-319-03469-0

Industrial Management- Control and Profit
A Technical Approach
Halevi, G.
2014, X, 273 p. 107 illus., Hardcover
ISBN: 978-3-319-03469-0