TOLERANCE DESIGN : EXPRESSING DESIGN INTENT IN DRAWINGS

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ABSTRACT: Despite the improvement in the performance of machine tools, the dimensions and shape may vary from part to part even if all parts have been processed in a similar manner. Efforts are made to minimize this discrepancy (variation or nonuniformity) in both design and manufacturing stages, however, it is impossible to completely eliminate the discrepancy. Basically, the dimension of parts varies above or below its target value. The allowable range of discrepancy should be determined considering all related factors, including the specifications and manufacturing cost of a product. Recently, we have often heard those involved in manufacturing say that all parts have been processed according to the instructions of designers but that those parts cannot be assembled or do not work after assembly. In many cases, this is because designers do not correctly understand what tolerance design is and they do not implement it in a proper manner. Also, for various reasons, designers do not have much access to the information about the requirements arising from manufacturing processes. These factors result in a negative spiral of an increased cost of failure and delay in the development of the next version of products. When designers specify a tolerance, they express their intent in drawings, comprehensively considering both the functions and performance expected of a product and the manufacturing cost. In this study, I will show that tolerance design, namely, the skill of being able to express the design intent in drawings, and geometrical tolerance, namely, the skill of being able to convey the intent correctly, work together as two wheels of a cart. Also, the skill of geometrical tolerance alone is not enough to create drawings that meet global standards. Geometrical tolerance should be based on correct tolerance design. A real example demonstrating this point is provided and discussed in this paper.

Keywords: Tolerance design, Global standard drawing, Geometrical tolerance.

1. INTRODUCTION

Vehicle recalls and market complaints about electric appliances are a source of concern for Japanese companies. They are attributed in part to “variation”, which will be reduced by proper tolerance design.

Noteworthy activities that are taking place in Japanese companies regarding tolerance design are the introduction of geometric dimensioning and tolerancing (GD&T). As a result of the revision of the Japanese Industrial Standards (JIS) in March 2016, applying GD&T to all drawings became indispensable. My concern is that some people desire only the application of GD&T to drawings, although few may have such a biased view. It is true that GD&T is essential. However, what most business managers really want is not merely to replace conventional drawings with the ones incorporating GD&T but a design revolution that will bring about an improved quality of drawings in which, for example, designers and engineers learn both tolerance design and GD&T.

In this study, I will show that tolerance design, namely, the skill of being able to express the design intent in drawings, and geometrical tolerance, namely, the skill of being able to convey the intent correctly, work together as two wheels of a cart. Also, the skill of geometrical tolerance alone is not enough to create drawings that meet global standards. Geometrical tolerance should be based on correct tolerance design. A real example demonstrating this point is provided and discussed in this paper.

2. TOLERANCE DESIGN

It is generally considered that discrepancy in the dimensions of parts is unavoidable and that it is acceptable if the final discrepancy is within the range of tolerance specified on drawings. This is how manufacturers understand tolerance. On the other hand, for designers, tolerance is something they must set with a sense of responsibility on the basis of a balanced view of product specifications, manufacturing conditions, and manufacturing cost. They should determine, from a comprehensive perspective, whether a product processed with the specified tolerance will meet the specifications of the final product and if the product can actually be processed with the specified tolerance.

In the actual design process, tolerances are determined as shown in Figure 1. In order for the specifications of finished products to be within a certain range of values, those of each unit must be within a certain range of values. Tolerances are allocated to each part in accordance with this range of values. This is the proper design process (1) where designers' intent is reflected.

In terms of finished products, more strict tolerances are desirable for making products smaller and thinner. In terms of ease (a cost reduction) of manufacturing parts, however, more relaxed tolerances are desirable. This is the requirement arising from (2) manufacturing processes. Naturally, cost increases when more strict tolerances are specified for individual parts. On the other hand, the risk of failure in finished products increases when more relaxed tolerances are specified, which may result in an increase in total cost in some cases.

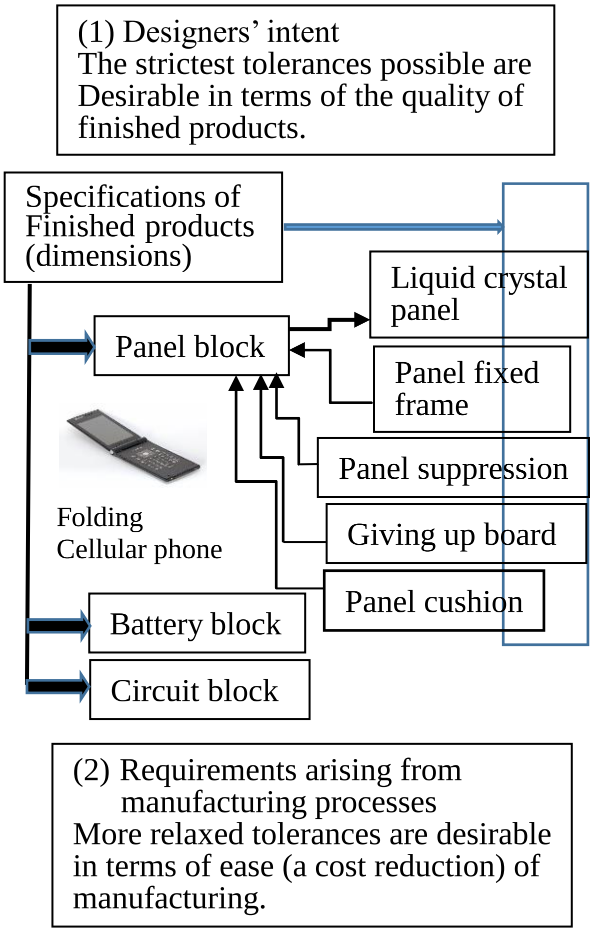

Figure 1: Determination of tolerances.

Tolerance is determined by balancing these two factors, the (1) designers' intent and the (2) requirements arising from manufacturing processes, which are projected onto a common axis, that is, economic efficiency (cost). The process of calculating and specifying tolerances while taking into account statistical information is called tolerance design.

Recently, designers do not often have much access to the information about the (2) requirements arising from manufacturing processes for various reasons such as the shift of production overseas. Under such circumstances, a system that facilitates a smooth exchange of (1) and (2) must be constructed in order to implement proper tolerance design.

2.1 Tolerance design and GD&T work together as two wheels of a cart

As mentioned above, tolerance design and GD&T work together as two wheels of a cart. When considered as two wheels of a cart, they can generate synergistic effects that bring about a better quality of drawings. As a result of the revision of JIS, the introduction of GD&T has become essential. The quality of drawings will be dramatically improved if GD&T is combined with tolerance design.

Most designers aim to achieve the following four goals in tolerance design.

1) Realization of product functions
2) Stabilization of product quality
3) Determination of part tolerances
4) Clarification of management priority points (points to be used as references, points to be controlled, and intended level of control)

Without achieving these goals, the quality of drawings will not be improved and neither can design revolution be realized. Tolerance design plays a crucial role in the accomplishment of design revolution.

The following is the mechanism of synergistic effects generated by the combination of tolerance design and GD&T. In a sense, GD&T is a common area whereas tolerance design is a competitive area. All designers must learn GD&T because it was adopted by JIS. However, there will be little differentiation in drawings if all designers master GD&T. What really affects the competitiveness of drawings is tolerance design because, in general, the know-how of tolerance design is accumulated and cultivated within an individual company. It is natural that the know-how of tolerance design, in other words, a source of competitiveness, is rarely provided to outsiders.

The proper tolerance design is therefore essential to enhance the competitiveness of drawings. Synergistic effects are generated by the combination of tolerance design and GD&T because the motivation of designers to learn GD&T will markedly increase as they learn tolerance design. Also, as designers learn tolerance design, they will become more aware of the necessity and significance of GD&T.

Namely, in tolerance design, designers identify the points in drawings that are to be used as references or to be elaborated. By repeating these steps, they can reduce waste, focus on necessary tolerances, and then specify those tolerances using GD&T. In time, a significant change will be seen in the drawings. The number of specified tolerances will markedly decrease and the number of items to be controlled in processing and measurement will also greatly decrease, resulting in a cost reduction and an improved quality of products.

2.2 Actual situation of tolerance design in Japanese companies

When asked, most managers in design departments will say that they are carrying out proper tolerance design. However, in fact, many Japanese companies do not or only partially carry out proper tolerance design. Very few designers and engineers have a full understanding of tolerance design and put it into practice. One of the reasons for this is that tolerance design is a competitive area, as described above.

There are few opportunities to learn tolerance design because it is a competitive area and accumulated know-how for a company. Designers rarely see how tolerance design is carried out in other companies, so the only opportunity to learn tolerance design is on-the-job training (OJT). However, recently, OJT is not working well in many companies.

Conventionally, designers used to carry out tolerance design, create drawings, and then bring them to production sites to ensure that the tolerance design is appropriate through discussion with engineers who are responsible for processing or measurement. Design departments stock many books on tolerance design that designers can refer to. They can also ask for the advice of more experienced designers when they are working on some key points in tolerance design.

Now, designers are incomparably busier than before. Experienced designers are so busy that they do not have time to teach young designers. In addition, OJT is not working as well as it used to be because three-dimensional (3D) CAD is used and previously created drawings are easily utilized or copied. The lack of understanding of tolerance design in design departments has not become such a big issue because it has been compensated by production departments. Now, however, there are fewer skilled engineers in production departments and designers cannot continue to depend on production departments.

For designers, tolerances are a very basic aspect of design. An increasing number of companies now encourage their employees to learn about tolerances all over again. The following is the current situation at manufacturing sites.

An alarming situation was revealed when young and skilled designers had gathered to discuss tolerance design. Young designers indeed really lack knowledge about tolerance, but skilled designers are not aware of this fact. Young designers often utilize the tolerances specified for similar parts that were manufactured in the past, even when they design completely new products (parts). Tolerance design may be a very basic skill for skilled designers but young designers lack knowledge about it.

2.3 Global manufacturing

The change in production sites is another reason why the issue of tolerance has recently become obvious. Under the circumstances of the know-how of tolerance design not being passed on to young designers and of tolerances not being properly specified, the key to maintaining the high-quality manufacturing in Japan was the excellent technological responsiveness at production sites. However, such technological responsiveness at production sites is no longer expected with production being shifted overseas. Any deficiency in design drawings leads directly to trouble. When the products (parts) are processed as directed in design drawings, that is, nothing more or nothing less than the values specified in the drawings, but do not work, the failure will result in extra cost to design departments. In fact, most of the trouble occurring at production sites overseas is a result of processing products just as directed in design drawings.

In order to promote global manufacturing and to manufacture high-quality products at low cost, there is an urgent need for Japanese companies to encourage their employees to learn about tolerances, the basic of drawings, all over again and to review the quality of drawings.

2.4 Merits of learning tolerance design

1) Acquiring ability to develop an appropriate design on the basis of the theory of tolerance calculation and criteria for judgment

In the study of the designers who say they do calculate tolerances, most of them answered that experienced designers taught them how to calculate tolerances (OJT) or that they learned it themselves. Many designers are often unsure about tolerance calculation and quite a few designers calculate tolerances improperly. If designers learn the theory of tolerance design systematically, they will become able to calculate tolerances with more confidence and to instruct younger designers proper tolerance calculation. The most difficult aspects in tolerance design are making judgments and taking appropriate measures. It is important to calculate basic tolerances, process capability indexes (*Cp* and *Cpk*), and percent defective properly and then to make judgements and take appropriate measures on the basis of the obtained values.

2) Acquiring ability to prevent design quality problems in a theoretical method before they arise

Once a product is designed, there is no need to wait for identifying issues until the product is actually manufactured; all details of the product are determined by the design. Referring to design drawings, engineers can easily know the kinds of defects (troubles and failures) that will occur and the probability of such defects (percent defective) if all parts are processed and assembled as directed in the drawings. This is called failure mode and effects analysis (FMEA). In tolerance design, designers calculate the probability of defects in each item and try to reduce that probability.

3) Acquiring ability to properly evaluate the designs of other designers

Leaders in design departments need to promptly evaluate the appropriateness of design drawings created by the designers working under them and give necessary advice (check of drawings). They should pay attention to some important design points and calculate the tolerances (manual calculation) of those points. If there seem to be any errors, it is necessary to review the tolerance calculation sheet created by the designers in charge. If there are any errors, the leaders should tell the designers what is wrong and how to fix it to make the design appropriate. For the leaders in design departments, these steps are crucial not only in checking drawings but also in coaching and developing young designers.

3. EXAMPLE OF TOLERANCE DESIGN

In this section, an example of the tolerance design of single-component products leading to cost reduction and the prevention of imitation is described.

When explaining the necessity of tolerance design, I am often asked about the significance of tolerance design for single-component products. Some may think that, if a product is to be manufactured only once, it is not necessary to specify a strict tolerance for each part in the design process because, even if the dimensions of parts are different from those specified in drawings, the parts can be modified or adjusted during assembly. This is, however, a big misunderstanding.

1) Demerits of modifications and adjustments.

Here, the demerits of modifications of parts or adjustments during assembly are described. Aside from the loss of time and cost spent in modifications and adjustments, the final quality of products is affected by the skills and sense of engineers because a flexible responsiveness is required in those processes. Although inspections are carried out after assembly to ensure the quality of products, there will be underlying differences in quality, which do not appear in drawings or specifications.

Also, it is common to manufacture a variety of products that are similar to a single-component product. Parts with exactly the same drawings or partly modified ones may be used for manufacturing similar products. If the information about the modifications and adjustments made in the manufacturing of a single-component product is not recorded on drawings but only stored in the memory of the persons who were in charge, some otherwise unnecessary modifications and adjustments must be repeated in the manufacturing of a similar single-component product. This issue may be partly solved by keeping a record of the modifications and adjustments, but this is hardly a fundamental solution because difficulties still exist in specifying and determining the range of their applications.

Moreover, the dependence on adjustments during assembly can lead to easy product imitation. If a product is designed on the premise that it will be adjusted during assembly, namely, if the performance or functions of the product are realized through some adjusting mechanisms prepared in the design process, such a product can be easily imitated by reverse engineering. The product can be imitated by copying the rough shape and dimensions of parts and then adjusting those parts to achieve the intended performance.

All the above issues can be solved by proper tolerance design in the design process. In other words, the role of tolerance design is to solve those issues. The reduction of man-hours spent on modifications and adjustments will lead to cost reduction. Unless drawings are leaked, the tolerances specified for each part will not be revealed, even by reverse engineering. The know-how to realize the performance and functions of the product is guarded.

2) Variation exists even in single-component product.

Tolerance design is the process of design taking into consideration variations of dimensions. For many people, the word "variation" brings up an image of a lot of parts of the same kind. The actual dimensions of a part are distributed centering around the dimensions specified in a drawing. Some may therefore think that variation does not exist in single-component products because they are manufactured only once.

However, variation does exist, even in single-component products. There are varying degrees of differences between the dimensions of processed parts and those specified in drawings. Variation is the degree and probability of such differences. In tolerance design, variation and its effects are estimated to determine the shape and dimensions of parts and, in some cases, to specify the allowable range of variation as a tolerance.

Similarly to the variation in mass products, the variation in single-component products can be estimated on the basis of process capability. Designers allocate tolerances for each part utilizing its full range of process capability. Unnecessarily strict tolerances or tolerances that always require modifications after processing or adjustments during assembly lead to cost increases. Designers should understand the accurate process capability of individual parts that make up the product they design. For this purpose, it is important to examine the information about the products manufactured in the past and to go to the production sites to obtain more information. Of course, it is necessary to review the process capability when any changes are made in the method of processing, the materials, and the manufacturers. These changes are generally called 4M (man, machine, material, and method) changes. How these changes are controlled is also important.

4. OVERVIEW OF GD&T AND MAXIMUM MATERIAL REQUIREMENT

4.1 From dimensional tolerances to GD&T

In global manufacturing, the final quality of parts must be ensured regardless of the country where the parts are processed, the experience of the persons processing the parts, and the machines used in processing. To realize this, the basic premise is to eliminate ambiguity in the specification of tolerances in drawings. The elimination of ambiguity will lead to the prevention of not only any unexpected decrease in the precision of products but also a cost increase due to an unnecessarily high precision of products.

The greatest reason of ambiguity remaining in drawings is that most tolerances are defined as dimensional tolerances. Figure 2 shows a rectangular front view and a rectangular side view for which the height, width, and depth are specified in the drawing. The engineer who creates this drawing expects a cuboid but the manufactured part rarely has a cuboid.

When dimensional tolerances are used, there remains the possibility that the processed shape will become irregular because the accuracy of a shape is basically checked by measuring the distance between two points. The ambiguity can almost be eliminated if the flatness of a plane and the parallelism and squareness with respect to a reference plane are defined by GD&T.

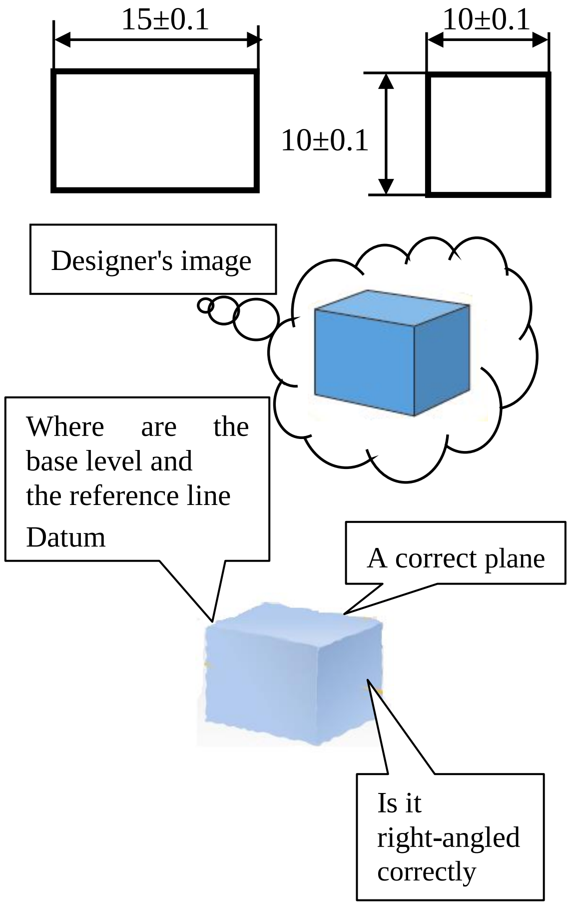

Figure 2: Ambiguity remaining in Drawings

Using dimensional tolerances, only a straight-line distance between two points is controlled, in principle. For example, when the tolerance of height is specified as 10±0.1 mm, the height must be within the range from 9.9 to 10.1 mm at any point. A shape can meet this dimensional tolerance requirement even if the top and bottom surfaces are considerably curved in the same direction while remaining parallel to each other or the side view of the shape is distorted like a parallelogram. Again, accurate manufacturing on the basis of dimensional tolerances has been possible because the persons working at production sites in Japan have sophisticated abilities to manufacture products with no bends or distortions even when it is not specifically directed.

To avoid irregular shapes such as those mentioned above, it is necessary to clearly define the flatness of a plane and the parallelism and squareness between two planes using GD&T. The shape, position, and location of points, lines, and planes including the flatness, which defines the evenness of a plane surface, and the squareness, which defines the vertical angle of a plane with respect to a reference plane, can be controlled using GD&T.

GD&T itself is not a new technique but has not been common in Japan because it had not been much needed, as explained above. Another barrier to the widespread use of this technique is that, compared with dimensional tolerances, many engineers find it more difficult to understand the concept of GD&T or how to give directions using this technique.

In the future, however, GD&T will become essential in the manufacturing industry in Japan, because designers should communicate their intent accurately and promptly in order to keep up with globalization and to meet the demands for quality improvement.

4.2 Overview of maximum material requirement

A circled M indicates the application of the maximum material requirement. By this method, GD&T values can be relaxed in conjunction with dimensional tolerances so that the number of conforming products can be increased (Figure 3).

There is a shaft of 10 mm in diameter. The dimensional tolerance for the diameter is specified as ±0.1 mm, and the straightness is specified as ϕ0.2 mm. In general, the straightness ϕ0.2 mm applies to every diameter of the shaft regardless of its dimension. With the application of the maximum material requirement, however, the straightness can be interpreted to be ϕ0.4 mm if the diameter of the shaft is 9.9 mm because it still meets the purpose of inserting the shaft into a hole of a certain diameter.

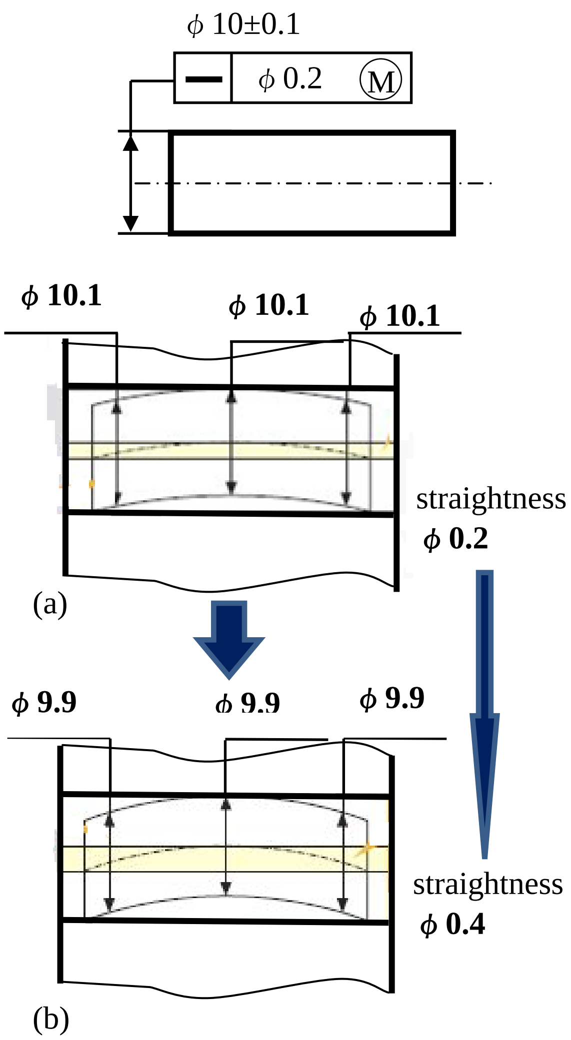

Figure 3: Example of maximum material requirement

Compared with dimensional tolerances, GD&T often requires higher precision in processing because it eliminates ambiguity. With the skillful use of GD&T, however, the parts that were conventionally identified as nonconforming products can be used as conforming products.
Dimensional tolerances and GD&T are basically independent of each other, but they are considered in conjunction with each other when maximum material requirement is applied. In short, maximum material requirement allows the relaxation of GD&T values in accordance with dimension values.
In the above example, the dimensional tolerance is specified as ϕ 10±0.1 mm and the straightness is specified as ϕ 0.2 mm in the drawing. Therefore, the external diameter of the shaft is 9.9–10.1 mm and the central axis of the shaft is within 0.2 mm in diameter. Here, we consider the purpose of specifying the tolerance for the shaft. For example, if the tolerance is required to insert the shaft into a hole, the primary purpose of specifying the tolerance is to be able to insert the shaft into the intended hole.
The following logic is true in this case. In order for all shafts processed as described above to be inserted into a hole, the hole must have a diameter of 10.3 mm or more [Figure 3 (a)] so that the shaft 10.1 mm in diameter with a bending central axis can be inserted into such a hole.
With a diameter of 9.9 mm, a shaft with a straightness of ϕ 0.4 mm or 0.2 mm can be inserted into such a hole [Figure 3 (b)].
Namely, if the purpose of specifying the tolerance is to insert the shaft into the intended hole, no trouble will arise if the requirement for straightness is relaxed in accordance with the shaft diameter.
As shown by this example, the maximum material requirement is used mainly to prevent interference between parts. Alternatively, GD&T can also be relaxed by using the lowest material requirement, which is often used for ensuring minimum thickness. By flexibly using these two methods in combination with GD&T, the number of nonconforming products can be decreased, leading to cost reduction.

5. CONCLUSION

Tolerance design and GD&T are essential in resolving the issues of variation in manufacturing, cost reduction, and prevention of trouble and failures such as malfunction and improper assembly of products manufactured overseas.

When designers have a correct understanding of tolerance and carry out tolerance design from the early stage of design, they can provide a well-balanced design, taking account of both quality and cost. Also, GD&T is essential for the correct expression of the design intent to later processes. However, the use of GD&T and education on it are lagging behind in Japan.

Ambiguity and differences in interpretations are removed from drawings when directions are appropriately provided using geometrical product specifications (GPS), which was discussed in the ISO/TC213, and GD&T, which is a universal design language. With such drawings, it is possible to prevent trouble such as a difference between the design intent and the finished product that commonly occurs, particularly when production sites are located overseas.

In addition, because of the revision of JIS in 2016, it became necessary to define the relative position of objects using not conventional dimensional tolerances but GD&T. Proper tolerance design and the application of GD&T are both essential for improving the quality and competitiveness of drawings.

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