Kasetsart J. (Nat. Sci.) 49 : 924 - 936 (2015)

New Practical Dimensioning Tolerance Allocation Technique for Assembly of Mechanical Parts

Kittichote Supakumnerd[1], Kamuttraiyoe Chutasen[2], Phaireepinas Phimpisan[3] and Chatchapol Chungchoo[3,*]

ABSTRACT

Currently, the assembly tolerance allocation of precision mechanical equipment can be determined by many methods such as engineer's experience, the worst on worst tolerance analysis method, the root sum square tolerance analysis method, or the Monte Carlo simulation method. However, there are other factors that need to be considered when engineers allocate individual tolerance values to each part. Examples of these factors include the production cost and the uncertainty of the measuring equipment. A new method for allocating a suitable tolerance value to each part or component was developed. By using a real industrial case study, the experimental results indicated that the new method could provide suitable component tolerance values for the production line. Compared with the leveling technique, the results also indicated that the new method can provide better tolerance values. However, this new method has a major limitation in that it can be used only for linear tolerance.

Keywords: design tolerance, machine performance, manufacturing tolerance, proportionality factor, tolerance allocation

INTRODUCTION

Currently, design engineers specify the tolerance of their product using the term "design tolerance". However, this tolerance is for the final product. If final products need to be assembled from several parts, production engineers themselves have to set the tolerance values for each part. The tolerance value employed in the production line is called the "manufacturing tolerance". Generally, the manufacturing tolerance can be specified from the allocation of design tolerance. Unfortunately, current tolerance allocation techniques are hard to use in production. The major objective of this research was to develop a new practical method for allocating tolerance values to parts for assembly. The study scope was defined by: 1) the assembly of mechanical parts as a case study; 2) the mechanical parts needed to be finished using machine tools; and 3) the expectation that this new technique could be used with high efficiency if the performance of the machine tools is known.

Relevant theory

In this paper, the important relevant theories are: 1) the difference between tolerance analysis and tolerance allocation; and 2) tolerance allocation methods.

[1] Department of Mechanical Engineering, Faculty of Engineering, Srinakharinwirot University, Nakhon Nayok 26120, Thailand.

[2] MEiPT Program, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.

[3] Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.

* Corresponding author, e-mail: fengcpc@ku.ac.th

Received date : 05/05/14 Accepted date : 10/06/15

Tolerance analysis versus tolerance allocation

Tolerance analysis is the calculation of assembly tolerance from the known component tolerance, while the tolerance allocation is a method to determine the tolerance value of each component from the known assembly tolerance (Chase, 1988, 1999), as shown in Figure 1. This summary agrees with Pawar *et al.* (2011).

Both tolerance analysis and tolerance allocation must consider assembly tolerance. Traditionally, there are six tolerancing approaches: consult standard tolerance analysis, worst-case tolerance analysis, statistical methods, sensitivity analysis, computer-aided tolerancing, and cost-based optical tolerance analysis (Pawar *et al.*, 2011). However, in manufacturing processes, there are two common approaches that are used for analyzing the assembly tolerance—worst limits analysis and statistical analysis (Chase, 1988,1999).

In worst limits analysis (the Worst on Worst Analysis Model or WOW), the assembly tolerance is determined by summing the component tolerances linearly. Each component is assumed to be at its maximum or minimum limit. The result is the possible assembly limits. On the other hand, in a statistical analysis, component tolerances add as the root sum of squares (RSS). The low probability of the worst case combination occurring is taken into account statistically. The distribution for component variations is assumed to be a Normal or Gaussion distribution (Chase, 1988, 1999).

It should be noted that a major assumption of the WOW model is that fluctuations can be combined in the worst possible way. This WOW method is time saving for a simple dimensional chain. Many manufacturers consider that it is a kind of over-design method which results in an increase in the manufacturing cost. However, for some complex assembly cases, this WOW model is the best assembly tolerance allocation method because theoretically, the final geometry of the assembly product will be in geometrical product specifications (Lin *et al.*, 1997).

Figure 2 shows an example of the difference between tolerance values calculated using WOW and RSS, in which it was found that the tolerance value from the WOW method is larger than the value from the RSS method.

Reviews of tolerance allocation

Several methods of tolerance allocation have been proposed.

Tolerance allocation by leveling technique

This technique is the simplest method for allocating tolerance values to each component (Altarazi, 2005). Sometimes, however, this method provides a too precise tolerance value for the component resulting in an increase in component cost (Altarazi, 2005). Figure 3 illustrates the use of the leveling technique for allocating tolerance values. In this example, it was found that for each subassembly, the tolerance value of each subassembly or component was decreased 10 times.

Tolerance allocation by proportional scaling

Initially, component tolerances can be assigned by using process or design guidelines. The component tolerances are summed to see if they meet the product's assembly tolerance. However,

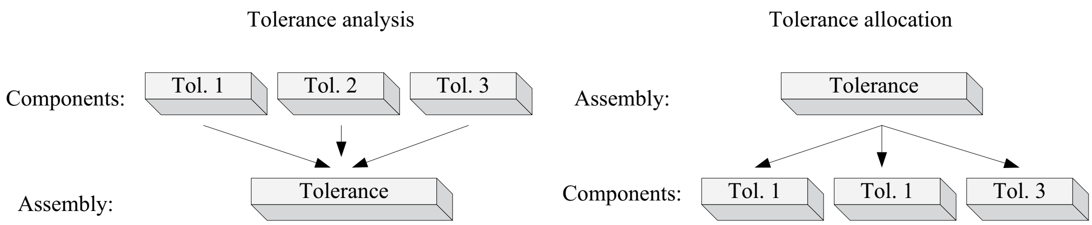


Figure 1 Tolerance analysis versus tolerance allocation.

if not, the tolerance of each part or component can be scaled by a constant proportionality factor. Using this technique, the relative magnitudes of the component tolerances are preserved (Chase, 1988, 1999; Altarazi, 2005; Kumar, 2010).

Tolerance allocation by constant precision factor method

This method allocates tolerances on the basis that the tolerances of parts are equal only if they are the same in size. The size is defined as the cube root of its length. Designers do not need prior knowledge of the natural tolerances of the individual parts of the assembly, making it useful in new part design with unknown natural

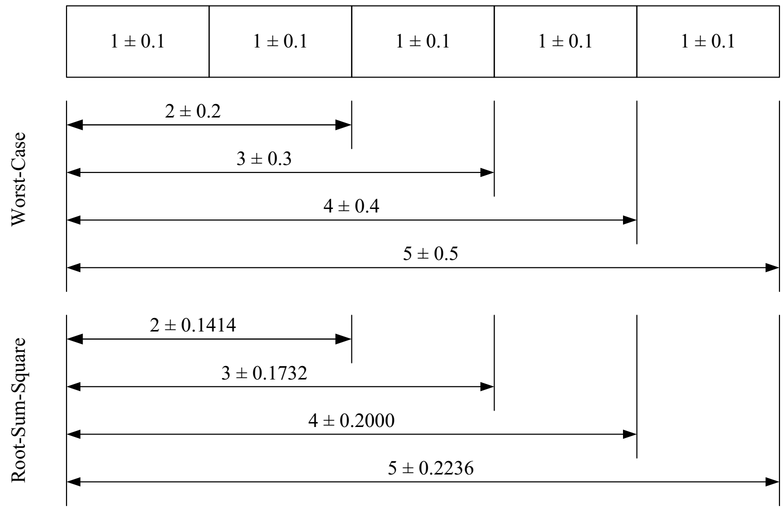


Figure 2 Tolerance ranges are monotonically increasing as assembly is built, based on the rigid-body assumption (resketching from Pawar *et al.*, 2011).

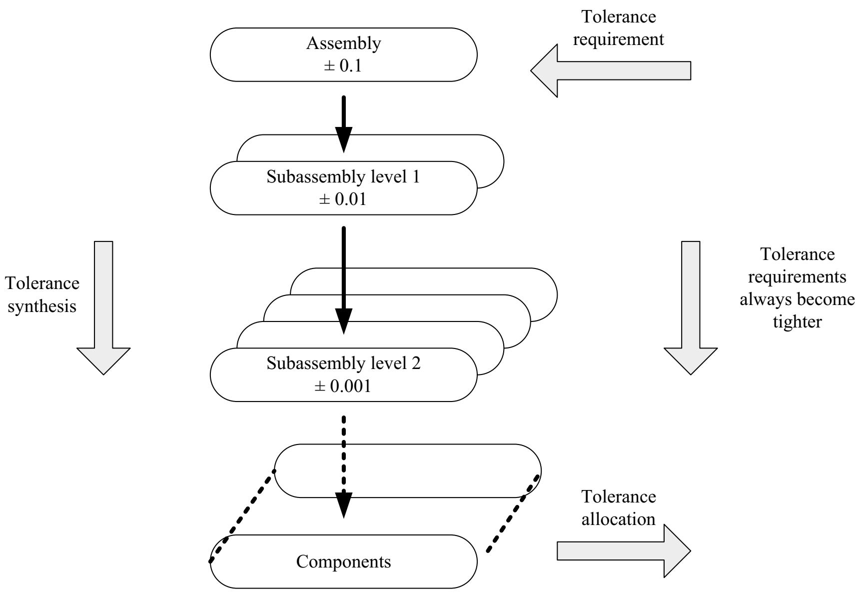


Figure 3 Example of tolerance allocation using leveling technique (resketching from Pawar *et al,.* 2011).

tolerances (Chase, 1988; Altarazi, 2005; Kumar, 2010).

Tolerance allocation by weight factors

Another method of assigning tolerances is the means of weight factors. The component tolerance can be assigned by weight factors to each tolerance in the chain and the system distributes a corresponding fraction of the tolerance pool to each component. However, designers need to take account of several parameters (such as manufacturing ability and cost) before assigning a weight factor to each component (Chase, 1999; Kumar, 2010).

Tolerance allocation using least cost optimization

Another method of tolerance allocation involves the evaluation of the machining costs of each component. The relationship between the machining costs and part tolerance is expressed through a mathematical formula, and the total machining cost is optimized to a minimum. It is subject to the constraints of the assembly function requirements. To achieve this, there is a need for cost tolerance data for each part in the assembly (Chase, 1988, 1999; Altarazi, 2005; Kumar, 2010).

Tolerance allocation by fuzzy comprehensive evaluation

The Fuzzy Comprehensive Evaluation (FCE) method was introduced by Kumar (2010). It is considered to incorporate better estimation of machining costs. In the FCE method, the machining costs are assumed to be dependent on certain fuzzy variables (such as shape and material) that are subjective in nature and have no numerical measure. These factors are modeled using fuzzy sets, and the FCE is used to calculate the machining difficulty of each part. A part with higher machining difficulty will be more expensive to machine and will have looser tolerances.

MATERIALS AND METHODS

Figure 4 shows a flow diagram of the new tolerance allocation method introduced in this paper. This begins with allocating a tolerance for each part following the recommended value indicated in ISO 2768-1 (ISO, 1989). This value is termed the initial tolerance allocation value. However, there is a chance that the sum of the initial tolerances is not equal to the design values. Hence, a stack-up initial tolerance needs to be adjusted to equal the design tolerance. Then, a proportionality factor (PF) has to be calculated. This PF can be determined from the design tolerance divided by the stack-up initial tolerance. Next, an initial manufacturing tolerance value of each part is assigned by multiplying the initial tolerance allocation value by the PF value. After that, production engineers have to decide which parts need to be bought-in and which parts can be produced in-house. For the manufactured parts, the manufacturing tolerance can be set by decreasing the initial manufacturing tolerance value by 10%. This number is a commonly used safety value (Henzold, 2006). However, the safety value must be greater than the sum of uncertainty of all measuring equipment. Finally, production engineers have to check if a given part can be made under this manufacturing tolerance value or not (by comparing the current machining accuracy with manufacturing tolerance). If not, a new tolerance value needs to be assigned.

New tolerance allocation method verification

In this research, the new tolerance allocation technique for the assembly of mechanical parts was verified by comparing its results with the results from the leveling technique which is a common technique employed in manufacturing (Altarazi, 2005). Figure 5 shows the case study using a precision slide, and is a real industrial application.

RESULTS

Example of industrial application

From Figure 5, there are six sections to

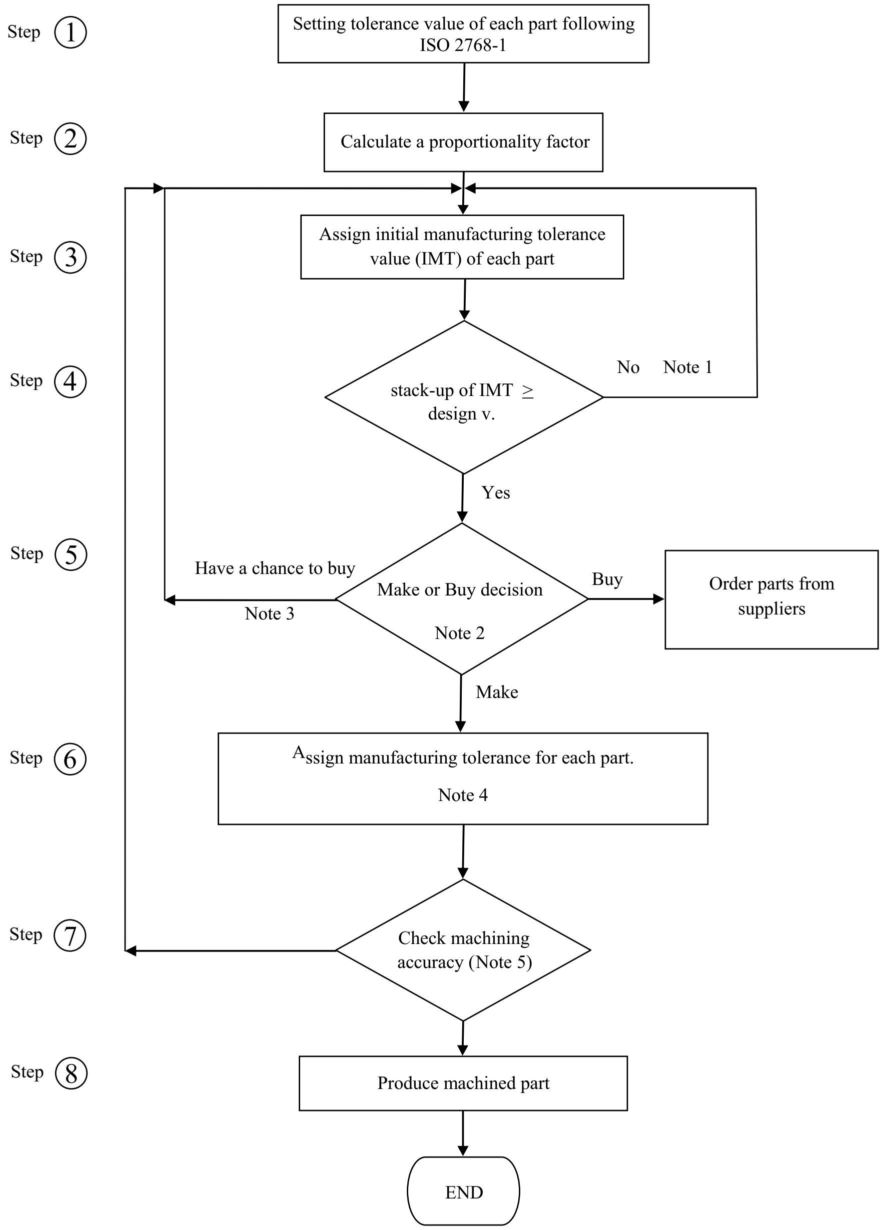


Figure 4 Flow diagram of the new tolerance allocation method. Note 1 Where the stack-up initial manufacturing tolerance is greater than the design value, the initial manufacturing tolerance of each part needs to be decreased in the same ratio until the stack-up initial manufacturing tolerance is lower than the design value. Note 2 Using the supplier's catalogue: Case 1: part tolerance from catalogue ≤ an initial manufacturing tolerance → order a part; Case 2: part tolerance from catalogue > an initial manufacturing tolerance → decide whether to purchase the part or produce in-house; Note 3 Reassign initial manufacturing tolerance value. Note 4 The manufacturing tolerance can be set by decreasing the initial manufacturing tolerance value 10% (safety value). If this safety value is not suitable, a greater number needs to be applied. Note 5 If available machines cannot produce the parts, tolerance values need to be reassigned.

be considered when the tolerance of each part is allocated. Details for these sections are shown in Figure 6. All tolerance values in both figures follow the industrial standard ISO 2768-1 (ISO, 1989). It should be noted that Figure 6 is a front view of Figure 5b, and all drawings in Figures 5 and 6 and in Tables 2–7 are sketches.

Example of calculations for the introduced technique and the leveling technique

Section A1 was selected as an example to explain clearly the calculation process of the new technique,. Employing the diagram shown in Figure 4, the calculation steps and the tolerance value for each step are indicated in Table 1. For the leveling technique applied to the same example, the calculation steps are shown in Figure 7.

Comparison of tolerance allocation using the new technique and the leveling technique

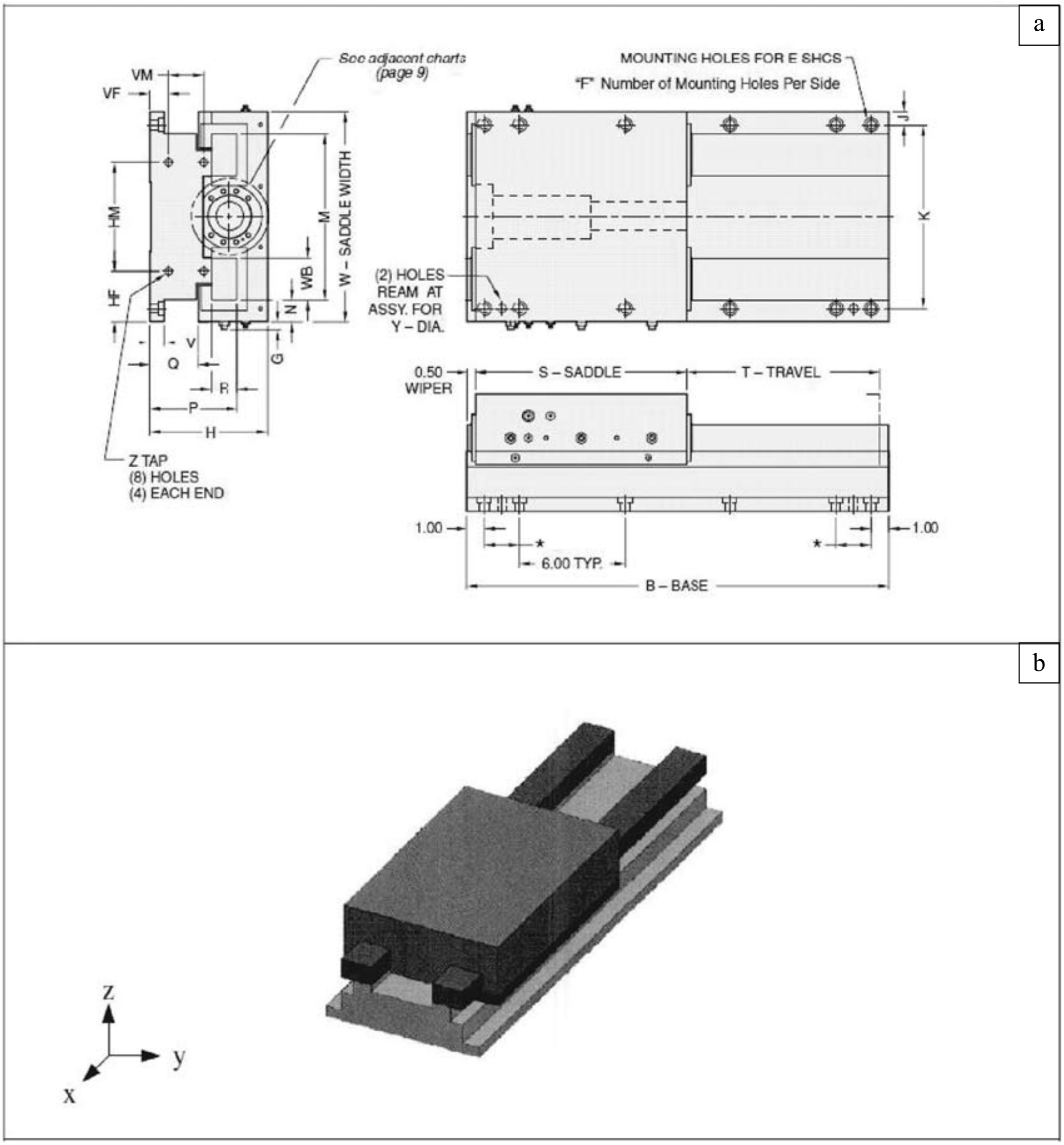


Figure 5 Case study of a precision slide: (a) Detailed technical drawings; (b) Solid model.

Tables 2–7 show comparisons between the tolerance allocation calculated from the new technique and tolerance allocation determined from the leveling technique starting with section A1 and finishing at section B2, respectively. Sections A1 to A4 concern the assembly of mechanical parts in the vertical direction, while sections B1 and B2 consider the horizontal direction. It can be observed that the tolerance values from the new method are larger than the value from the leveling technique. Manufacturers spend less money in production for machined parts with larger tolerance values. Hence, manufacturers will prefer to use tolerance values determined from the new method rather than values from the leveling technique.

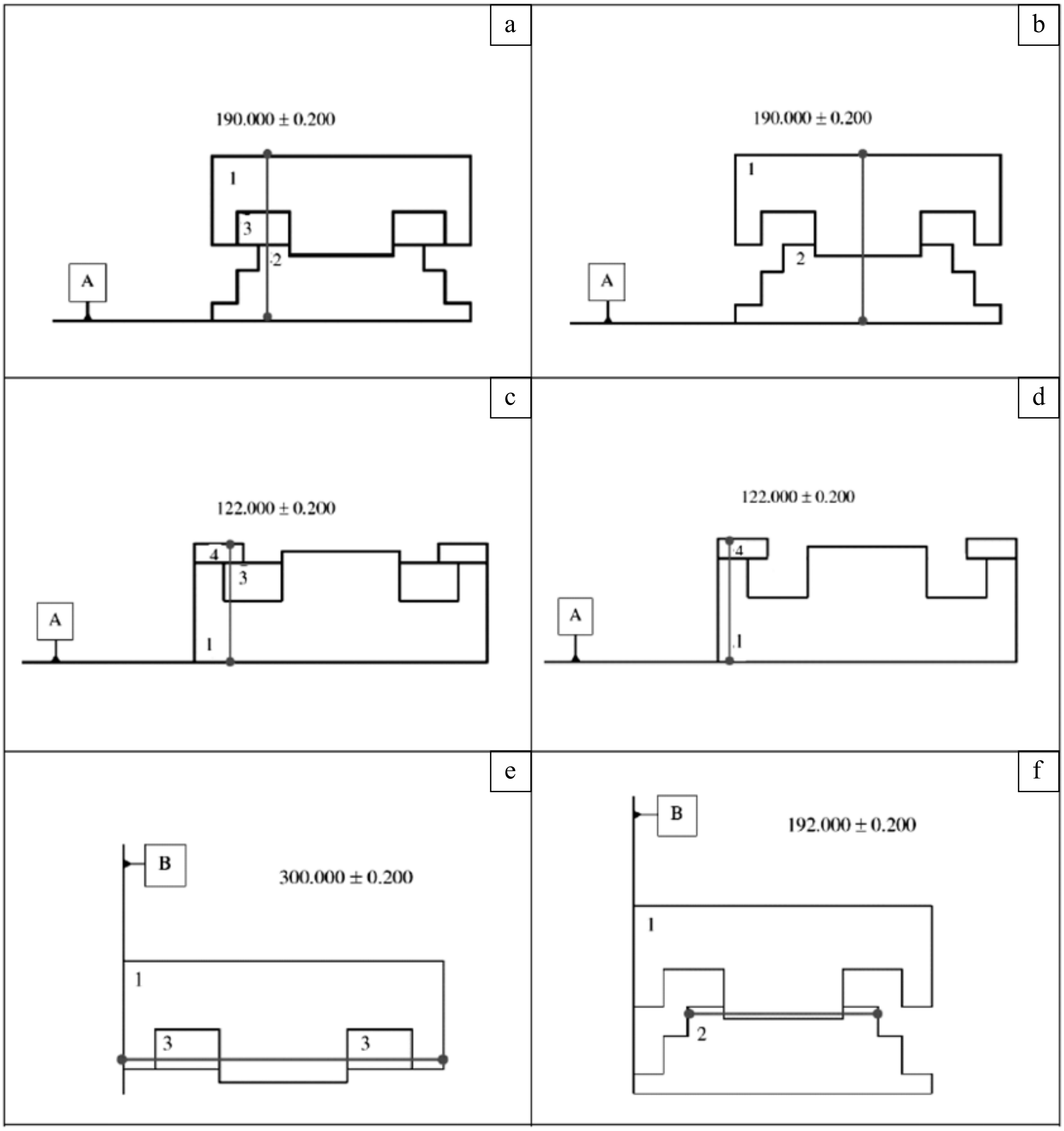


Figure 6 Six important sections for tolerance allocation: (a) Section A1 (190.000 ± 0.200 mm); (b) Section A2 (190.000 ± 0.200 mm gap 0.500 mm); (c) Section A3 (122.000 ± 0.200 mm); (d) Section A4 (122.000 ± 0.200 mm); (e) Section B1 (300.000 ± 0.200 mm); (f) Section B2 (192.000 ± 0.200 mm). The lines with circled ends indicate the points of measurement.

Table 1 Tolerance allocation of section A1 using the new technique.

Assambly size	Iteration	Part	Stack-up of IMT	Step (1)	Step (2)	Step (3)	Total design V.	Step (4)	Step (5)	Safety value 10%	Step (6)	Step (7)	2((6) + (7))	Assign tolerance	Step (8)	Remark
Subclass 2 190.000 ± 0.200 mm	1	Part 1	0.200	0.150		0.150	0.350	IMT< Total design V.								
		Subclass 1		0.200		0.200										
	2	Part 1*			0.571	0.086	0.200	IMT ≥ Total design V.	Make	0.0086	0.0004	0.0043	0.0051	0.0771	end	To use safety value 10%
		Subclass 1			0.571	0.114										
Subclass 1 126.000 ± 0.114 mm	1	Part 2	0.114	0.150		0.150	0.300	IMT< Total design V.								
		Part 3		0.150		0.150										
	2	Part 2**			0.381	0.057	0.114	IMT ≥ Total design V.	Make	0.0057	0.0004	0.0059	0.0067	0.0504	end	To use tolerance design
		Part 3			0.381	0.057			Make	0.0057	0.0004	0.0025	0.0033	0.0514	end	To use safety value 10%

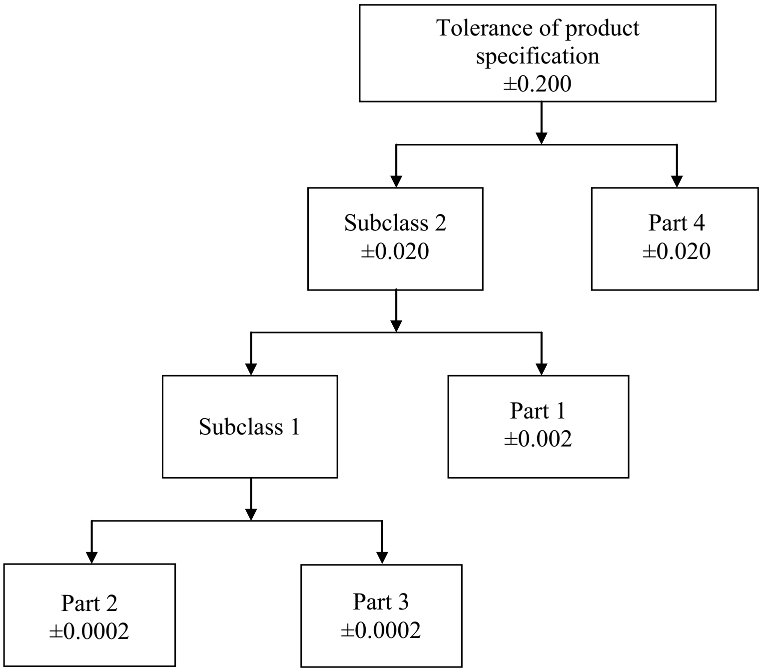


Figure 7 Tolerance allocation of section A1 using the leveling technique.

Table 2 Comparison of tolerance allocation from the new technique and the leveling technique: section A1 (mm). The lines with circled ends indicate the points of measurement.

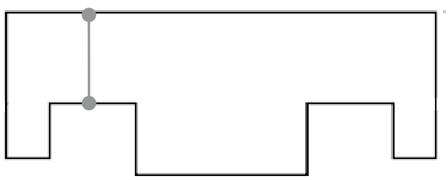
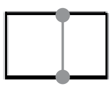
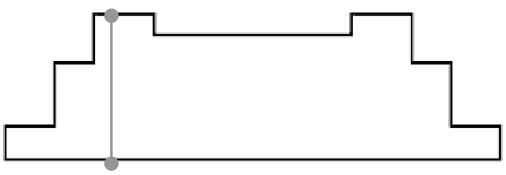
Part	View	Leveling Technique	New Technique
1		±0.0020	±0.0771
3		±0.0002	±0.0514
2		±0.0002	±0.0504
	Total tolerance design	±0.0022	±0.1789

Table 3 Comparison of tolerance allocation from the new technique and the leveling technique: section A2 (mm).). The lines with circled ends indicate the points of measurement.

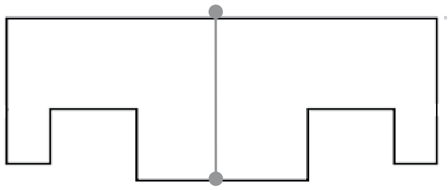
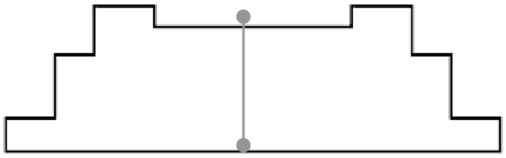
Part	View	Leveling Technique	New Technique
1		±0.0200	±0.1350
2		±0.0200	±0.1350
	Total tolerance design	±0.0400	±0.2700

Table 4 Comparison of tolerance allocation from the new technique and the leveling technique: section A3 (mm). The lines with circled ends indicate the points of measurement.

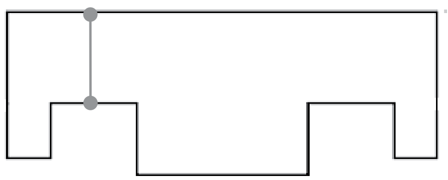
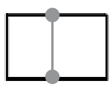
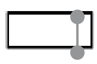
Part	View	Leveling Technique	New Technique
1		±0.0200	±0.0643
3		±0.0200	±0.0514
4		±0.0200	±0.0643
	Total tolerance design	±0.0600	±0.1800

Table 5 Comparison of tolerance allocation from the new technique and the leveling technique: section A4 (mm). The lines with circled ends indicate the points of measurement.

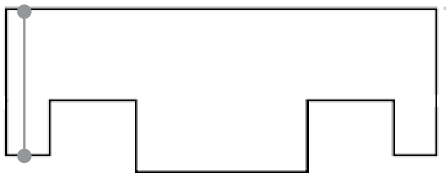
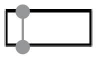
Part	Picture	Leveling Technique	New Technique
1		±0.0200	±0.1157
4		±0.0200	±0.0643
	Total tolerance design	±0.0400	±0.1800

Table 6 Comparison of tolerance allocation from the new technique and the leveling technique: section B1 (mm). The lines with circled ends indicate the points of measurement.

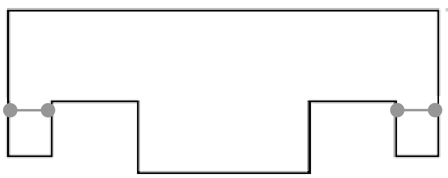
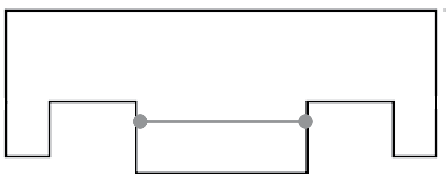
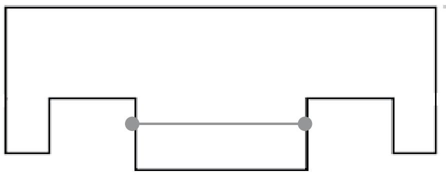
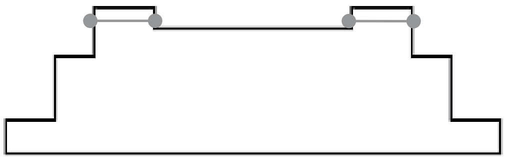
Part	View	Leveling Technique	New Technique
1		±0.0200	±0.0338
1		±0.0200	±0.0411
3		±0.0200	±0.0327
	Total tolerance design	±0.1000	±0.1741

Table 7 Comparison of tolerance allocation from the new technique and the leveling technique: section B2 (mm). The lines with circled ends indicate the points of measurement.

Part	View	Leveling Technique	New Technique
1		±0.0200	±0.0411
2		±0.0200	±0.0675
	Total tolerance design	±0.0600	±0.1761

DISCUSSION

The flow diagram in Figure 4 has four interesting points. The first point is that the initial tolerance value for each part is a common value recommended in ISO 2768-1 (ISO, 1989). This means that no special tolerance allocation experience is required in this step. Secondly, the fifth step of the flow diagram allows production engineers to make decisions over which parts can be bought and which parts need to be made. The third point concerns the safety value (10% of the initial manufacturing tolerance mentioned in Note 4 in Figure 4). This safety value is to ensure that the exact dimension of a part does not exceed an allowed limit due to the uncertainty of all measuring equipment. The final point involves the estimation of machining accuracy in the seventh step, whereby each machine needs to use its own technique for estimating machining accuracy. For example, the CNC turning centre and CNC machining centre, a technique described by Chungchoo (2013a, b) can be used to predict the final dimensions of a part.

Tables 2–7 indicate that the tolerance values of the new technique are greater than those determined using the leveling technique. Due to the fact that a part with a smaller tolerance has a higher production cost than the same part with bigger tolerance, parts with their tolerance values determined from the new technique have a lower production cost. However, the new technique requires a greater calculation time than the leveling technique.

It should be noted that the introduced tolerance allocation technique presented in this paper can be used for linear tolerances only. It cannot be used in the case of geometric tolerance such as tolerance of form, tolerance of profile, tolerance of orientation, tolerance of location and tolerance of runout.

CONCLUSION

A new practical technique for tolerance allocation was introduced which considers the effect of measurement uncertainty and the machining accuracy. Based on a real industrial case study of a precision slide, it was found that this method could provide suitable component tolerance values for the production line. A major benefit of this new method is that no highly experienced production engineers are required to implement this technique. However, the new method can be used for dimension tolerance only and cannot be applied to geometric tolerance.

ACKOWLEDGEMENTS

The authors would like to thank Kasetsart University for a supporting research grant.

LITERATURE CITED

Altarazi, S.A. 2005. **Operational Tolerance Allocation and Machine Assignment under Process Capability and Product Value Constraints.** PhD dissertation. Wichita State University. KS, USA. 144 pp.

Chase, K.W. 1988. Design issues mechanical tolerance analysis. **ADCATS Report.** 87: 1–9.

Chase, K.W. 1999. Tolerance allocation methods for designers. **ADCATS Report.** 99: 1–34.

Chungchoo, C. 2013a. An application of finished test pieces in ISO 10791-7 for performance evaluation of CNC machining centres. **Proceedings of the 4th TSME International Conference on Mechanical Engineering (TSME-ICOME 2013).** Organized by Burapha University, Thailand. 16–18 October 2013. Pattaya. Chonburi. CD-ROM.

Chungchoo, C. 2013b. An application of finished test pieces in ISO 13041-6 for performance evaluation of CNC turning centres. **Proceedings of the 4th TSME International Conference on Mechanical Engineering (TSME-ICOME 2013).** Organized by Burapha University, Thailand. 16–18 October 2013. Pattaya. Chonburi. CD-ROM.

Henzold, G. 2006. **Geometrical Dimensioning and Tolerancing for Design, Manufacturing and Inspection: A Handbook for Geometrical Product Specifications using ISO and ASME Standards.** 2nd ed. Butterworth-Heinemann. Amsterdam, the Netherlands. 389 p.

ISO. 1989. **ISO 2768-1:1989 General Tolerances – Part 1: Tolerances for Linear and Angular Dimensions without Individual Tolerance Indications.** International Organization for Standardization. Geneva, Switzerland.

Kumar, A. 2010. **A Tolerance Allocation Framework Using Fuzzy Comprehensive Evaluation and Decision Support Processes.** MSc. Thesis, Georgia Institute of Technology. Atlanta, GA, USA. 130 pp.

Lin, C.Y., W.H. Huang, M. C. Jeng, and J. L. Doong, 1997. Study of an assembly tolerance allocation model based on Monte Carlo simulation. **J. Mat. Proc. Tech.** 70: 9–16.

Pawar, S.Y., H.A. Chavan, and S.P. Chavan, 2011. Tolerance stack up analysis and simulation using visualization VSA, **Int. J. Adv. Eng. Tech.** 2: 169–175.