The 6th TSME International Conference on Mechanical Engineering
16-18 December 2015

AMM024

A Study on Tolerance Design for Machine Tools based on Shape Generation Functions

Ryo TAKEMATSU[1,*], Nobuhiro SUGIMURA[1] , Arata YOSHIDA[1]
Wiroj THASANA[2] , Yoshitaka TANIMIZU[1] and Koji IWAMURA[1]

[1]Osaka Prefecture University, 1-1Gakuen-cho Naka-ku, Sakai-shi, Osaka, Japan, 599-8231
[2]Thai-Nichi Institute of Technology, 1771/1, Pattanakarn Rd, Suan Luang, Bangkok, 10250, THAILAND
*Corresponding Author: sv101036@edu.osakafu-u.ac.jp, +81722549211

Abstract

Machining accuracy is one of the most important characteristics of 5-axis machining centers for generating the products with the high accuracy and the complicated geometries. Some researches have been carried out to analyze the machining accuracy of the machine tools based on the shape generation motions between the tools and the workpieces. The kinematic motion deviations of the 5-axis machining centers are deeply influenced by the geometric deviations of the components, such as guide ways and bearings. The machining accuracy can be improved by improving accuracy of the geometric deviations of the components. However, on the view point of manufacturing, effective geometric tolerance design is essential to reduce manufacturing cost.

The objective of this research is to establish a mathematical model which is applicable to the analysis of kinematic motion deviations of 5-axis machining centers based on the tolerances of the guide ways. A systematic procedure is proposed to determine the tolerance values of the guide-ways theoretically under the constraints on the basis of the kinematic motion deviations of 5-axis machining centers by applying ISO Tolerance definitions. The proposed method provides us with theoretical way to design the geometric tolerances of guide-ways connecting the components of five-axis machining centers, based on allowance of the kinematic motion deviation of the tools against the workpieces.

Keywords: 5-axis Machining Centers, Shape Generation Motions, Geometric Tolerances, Tolerance Design, ISOTolerance

1. Introduction

The kinematic motion deviations of 5-axis machining centers are deeply influenced by the geometric deviations of the components, such as guide ways and bearings. A systematic design method is required for specifying suitable geometric tolerances of the guide ways, in order to improve the kinematic motion deviations of 5-axis machining centers.

Many researches have been carried out to model and to analyze the machining errors of the machine tools, such as modeling shape generation motions of machine tools and machining error measurements [1-4]. These researches mainly focused on the analysis of the influences of the kinematic motion deviations of machine tool components on the kinematic motion deviations of the tools against workpieces and the geometric deviations of the machined surfaces.

In the previous paper [5], a system was proposed to design a suitable set of geometric tolerances of guide- ways considering the relation between the requirements on the kinematic motion deviations and the ease of manufacturing processes. The proposed method is based on the mathematical model of 5-axis machining centers proposed in the previous papers. However, the trade-off between the requirements on the kinematic motion deviations and the ease and the cost of the manufacturing process was not represented theoretically.

The objective of the present research is to establish systematic procedure which determine the tolerance values of the guide-ways theoretically under the constraints on the basis of the kinematic motion deviations of 5-axis machining centers by applying ISO Tolerance. The proposed method provides us with theoretical way to design the geometric tolerances of guide-ways connecting the components of five-axis machining centers, based on allowance of the kinematic motion deviation of the tools against the workpieces.

2. Geometric Tolerances and Deviations of Features[6-8]

The geometric tolerances of the features specify the allowable areas named “tolerance zones,” which constrain the position and orientation deviations of the associated features against the nominal features, as shown in Fig. 1 (a). The associated features and the nominal features mean the features of the manufactured products and the ideal features defined in the design phase, respectively. The geometric deviations of the associated features from the nominal features are represented by sets of parameters named “deviation parameters [6].” For example, one position parameter w and two rotational parameters α and β are required to represent the geometric deviations of the associated plane features against the nominal plane features, for the case where the tolerance zone is given by the area between a pair of parallel planes. In the research, the followings are assumed for the ease of the modeling and the analysis of the geometric deviations.

AMM024

(1) The deviation parameters δ_i representing the position and orientation deviations of the associated features follow the normal distribution $N(\mu_i, \sigma_i)$, and $\mu_i = 0$. Where, μ_i and σ_i are the mean values and the standard deviations, respectively.
(2) The manufacturing processes of the components are well controlled, and the proportion of the non-conforming components, which means the toleranced features exceed the tolerance zones, is as small as a value Pd called "percent defective".
(3) Equation (1) represents the relationships between the standard deviations σ_i of the deviation parameters of the tolerance features and the maximum values of the deviation parameters.

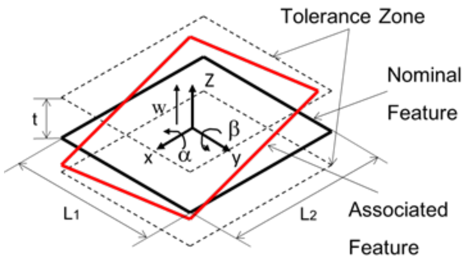
$$\sigma_i = \delta_{imax} / C_{pd} \tag{1}$$

where,
δ_{imax}: Maximum values of the deviation parameters δ_i, if the other deviation parameters are $\delta_j = 0$, $(i \neq j)$.
C_{pd}: A constant representing the ratio of the maximum values δ_{imax} and the standard deviations σ_i.

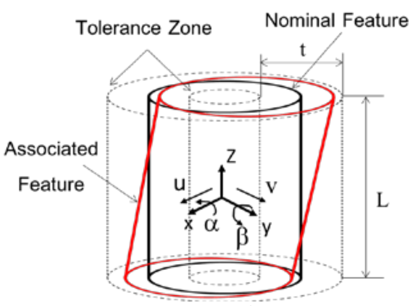
Let us consider a case shown in Fig. 1 (a), as an example. The maximum values δ_{imax} are given as follows.

$$\delta_1 = w,\ \delta_2 = \alpha,\ \delta_3 = \beta$$
$$\delta_{1\max} = \frac{t}{2},\ \delta_{2\max} = \frac{t}{L_1},\ \delta_{3\max} = \frac{t}{L_2} \tag{2}$$

where,
L_1, L_2: Length and width of the plane feature.
t: Tolerance values, e.g. the distance between two planes representing the tolerance zones.
From Eq. (1), (2), standard deviation of the deviation parameters are given as follows.



(a) Plane feature



(b) Cylinder feature

Fig.1 Definition of geometric tolerance of feature

$$\sigma_1 = t/2C_{pd},\ \sigma_2 = t/L_2C_{pd},\ \sigma_3 = t/L_1C_{pd} \tag{3}$$

The following equation gives the conditions that the plane features are included within the tolerance zone between a pair of planes.

$$-t/2 < \delta_1 + L_1\delta_2/2 + L_2\delta_3/2 < t/2 \tag{4}$$

The probability that the toleranced features are included within the tolerance zones is given by the following equation.

$$1 - P_d = \left(\frac{2}{\sqrt{2\pi}}\right)^3 \int_0^{C_{Pd}} \int_0^{C_{Pd}-x_1} \int_0^{C_{Pd}-x_1-x_2} \left(\prod_{i=1}^{3} \exp\left(-\frac{x_i^2}{2}\right)\right) dx_3 \tag{5}$$

where,

$$x_1 = 2C_{Pd}\delta_1/t,\ x_2 = 2L_1C_{Pd}\delta_2/t,\ x_3 = 2L_2C_{Pd}\delta_3/t$$

If the percent defective Pd is less than 0.27%, the constant C_{pd} can be estimated as "C_{pd} = 5.83," through the numerical analysis of Eq. (5).

In the case of a cylinder shown in Fig.1 (b), the following equation gives the standard deviation of the deviation parameter.

$$\begin{aligned} &\delta_1 = u,\ \delta_2 = v,\ \delta_3 = \alpha,\ \delta_4 = \beta \\ &\sigma_1 = \sigma_2 = t/2C_{pd},\ \sigma_3 = \sigma_4 = t/LC_{pd} \end{aligned} \tag{6}$$

In this case, the C_{pd} is estimated as "C_{pd}= 5.06," if the percent defective P_d is set to be 0.27%.

3. Modeling of Kinematic Motions of 5-axis Machining Center

The Kinematic motion matrix is formulated by relative kinematic motion deviations among table and base part of components, which it's predicted from geometric deviations of guide-ways and priority relationship between guide-ways.
The method to obtain geometric deviations of guide-ways from geometric tolerances, based on position and orientation deviations of features, are explained in previous section.

3.1 Modeling of Linear Tables[7]

The model and kinematic motion matrix of X-axis linear table are shown in Fig. (2) and Eq. (7). The equations for Y and Z-axis are also formulated in the same manner.

$$\mathbf{A}^1(x) = \begin{pmatrix} 1 & -\delta\gamma_x & \delta\beta_x & x \\ \delta\gamma_x & 1 & -\delta\alpha_x & \delta y_x \\ -\delta\beta_x & \delta\alpha_x & 1 & \delta z_x \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{7}$$

where,
x: X-direction travel
δy_k^x, δz_a^x: Position deviations of guide-way k(k=a, b, c, d)
α_k^x, β_k^x, γ_k^x: Orientation deviations of guide-way k(k=a, b, c, d)
β_{ia}^x, γ_{ib}^x: orientation deviations of guide-way k in Unit-i (k=a, b, c, d)

AMM024

$$\delta\alpha_x = \frac{1}{2}(\alpha_a^x + \alpha_c^x)$$

$$\delta\beta_x = \frac{1}{2}(\beta_a^x + \beta_c^x)$$

$$\delta\gamma_x = \frac{1}{2}(\gamma_b^x + \gamma_d^x)$$

$$\delta y_x = \frac{1}{2}\{(\gamma_{ib}^x + \gamma_{id}^x)x + (\delta y_b^x + \delta y_d^x)\}$$

$$\delta z_x = \frac{1}{2}\{-(\beta_{ia}^x + \beta_{ic}^x)x - (l_{ay}^x\alpha_a^x + l_{cy}^x\alpha_c^x) + (\delta z_a^x + \delta z_c^x)\}$$

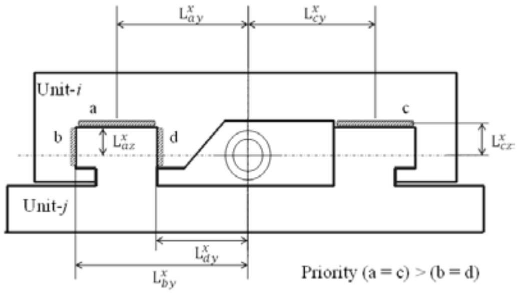


Fig.2 Model of X-axis linear table

3.2 Modeling of Rotary Tables[9]

There are two types for rotary motion tables. The model and kinematic motion matrix of C-axis (vertical axis) rotary table are shown in Fig.3 and Eq. (7), and A-axis (horizontal axis) rotary table are shown in Fig. 4 and Eq. (8).

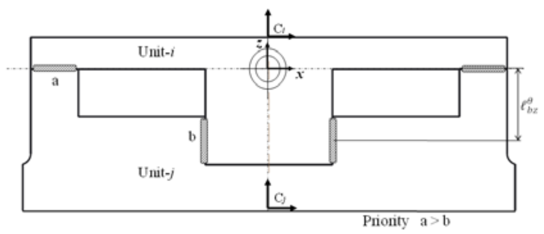


Fig.3 C-axis Rotary table

$$\mathbf{A}^6(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & \delta\beta_{\theta j} & \delta x_\theta \\ \sin\theta & \cos\theta & \delta\alpha_{\theta j} & \delta y_\theta \\ \delta\beta_{\theta i} & \delta\alpha_{\theta i} & 1 & \delta z_\theta \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (8)$$

where,
θ: Rotation angle of table
δx_{ks}^θ, δy_{ks}^θ, δz_{ks}^θ : Position deviations of guide-way k in Unit-s (k=a, b; s=i, j)
α_{ks}^θ, β_{ks}^θ, γ_{ks}^θ : Orientation deviations of guide-way k in Unit-s (k=a, b; s=i, j)

$$\delta\alpha_{\theta i} = \beta_{ai}^\theta \sin\theta + \alpha_{ai}^\theta\cos\theta - \alpha_{aj}^\theta$$

$$\delta\alpha_{\theta j} = -\beta_{aj}^\theta \sin\theta + \alpha_{aj}^\theta\cos\theta - \alpha_{ai}^\theta$$

$$\delta\beta_{\theta i} = -\beta_{ai}^\theta\cos\theta + \alpha_{ai}^\theta \sin\theta + \beta_{aj}^\theta$$

$$\delta\beta_{\theta j} = -\beta_{aj}^\theta\cos\theta - \alpha_{aj}^\theta \sin\theta + \beta_{ai}^\theta$$

$$\delta x_\theta = -\delta x_{bj}^\theta\cos\theta + \delta y_{bj}^\theta \sin\theta + \delta x_{bi}^\theta - l_{bz}^\theta(\alpha_{bj}^\theta \sin\theta + \beta_{bj}^\theta\cos\theta - \beta_{bi}^\theta)$$

$$\delta y_\theta = -\delta x_{bj}^\theta \sin\theta - \delta y_{bj}^\theta\cos\theta + \delta x_{bi}^\theta - l_{bz}^\theta(\beta_{bj}^\theta \sin\theta - \alpha_{bj}^\theta\cos\theta + \alpha_{bi}^\theta)$$

$$\delta z_\theta = \delta z_{ai}^\theta - \delta z_{aj}^\theta$$

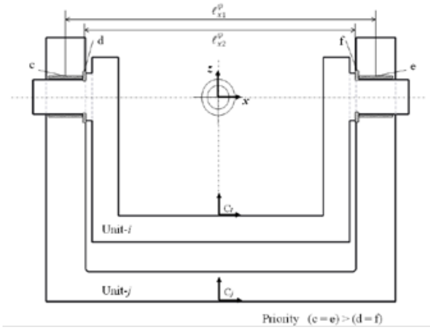


Fig.4 A-axis Rotary table

$$\mathbf{A}^4(\varphi) = \begin{pmatrix} 1 & \frac{1}{2}\delta\gamma_{\varphi i} & \frac{1}{2}\delta\beta_{\varphi i} & \frac{1}{2}\delta x_\varphi \\ \frac{1}{2}\delta\gamma_{\varphi j} & \cos\varphi & -\sin\varphi & \frac{1}{2}\delta y_\varphi \\ \frac{1}{2}\delta\beta_{\varphi j} & \sin\varphi & \cos\varphi & \frac{1}{2}\delta z_\varphi \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (9)$$

where,
φ: Rotation angle of table
δx_{ks}^φ, δy_{ks}^φ, δz_{ks}^φ : Position deviations of guide-way k in Unit-s (k=c, d, e, f; s=i, j)
α_{ks}^φ, β_{ks}^φ, γ_{ks}^φ : Orientation deviations of guide-way k in Unit-s (k=c, d, e, f; s=i, j)

$$\delta\beta_{\varphi i} = -\beta_{cj}^\varphi - \beta_{ej}^\varphi + (\gamma_{ci}^\varphi + \gamma_{ei}^\varphi)\sin\varphi + (\beta_{ci}^\varphi + \beta_{ei}^\varphi)\cos\varphi$$

$$\delta\beta_{\varphi j} = -\beta_{ci}^\varphi - \beta_{ei}^\varphi - (\gamma_{cj}^\varphi + \gamma_{ej}^\varphi)\sin\varphi + (\beta_{cj}^\varphi + \beta_{ej}^\varphi)\cos\varphi$$

$$\delta\gamma_{\varphi i} = \gamma_{cj}^\varphi + \gamma_{ej}^\varphi - (\gamma_{ci}^\varphi + \gamma_{ei}^\varphi)\cos\varphi + (\beta_{ci}^\varphi + \beta_{ei}^\varphi)\sin\varphi$$

$$\delta\gamma_{\varphi j} = \gamma_{ci}^\varphi + \gamma_{ei}^\varphi - (\gamma_{cj}^\varphi + \gamma_{ej}^\varphi)\cos\varphi - (\beta_{cj}^\varphi + \beta_{ej}^\varphi)\sin\varphi$$

$$\delta x_\varphi = \delta x_d^\varphi + \delta x_f^\varphi$$

$$\begin{aligned}\delta y_\varphi = &-l_{x1}^\varphi\{(\gamma_{ei}^\varphi - \gamma_{ci}^\varphi) - (\gamma_{ej}^\varphi - \gamma_{cj}^\varphi)\cos\varphi - (\beta_{ej}^\varphi - \beta_{cj}^\varphi)\sin\varphi\} \\ &- (\delta y_{cj}^\varphi + \delta y_{ej}^\varphi)\cos\varphi + (\delta z_{cj}^\varphi + \delta z_{ej}^\varphi)\sin\varphi + (\delta y_{ci}^\varphi + \delta y_{ei}^\varphi)\end{aligned}$$

$$\begin{aligned}\delta z_\varphi = &\, l_{x1}^\varphi\{(\beta_{ei}^\varphi - \beta_{ci}^\varphi) - (\beta_{ej}^\varphi - \beta_{cj}^\varphi)\cos\varphi + (\gamma_{ej}^\varphi - \gamma_{cj}^\varphi)\sin\varphi\} \\ &- (\delta y_{cj}^\varphi + \delta y_{ej}^\varphi)\sin\varphi - (\delta z_{cj}^\varphi + \delta z_{ej}^\varphi)\cos\varphi + (\delta y_{ci}^\varphi + \delta y_{ei}^\varphi)\end{aligned}$$

3.3 Modeling of 5-axis machining centers

Three types of 5-axis machining centers shown in Fig.5 are considered in this paper. The individual machining centers have the following characteristic features. The type-1 has two-axis rotary tables on the top of the linear tables, is not suitable for the large and heavy workpieces. However, it has high chip removal capability, and is suitable to high productive machining.

The type-2 has no rotary axis in the workpiece side, and in suitable for large and heavy workpieces. However, the spindle rigidity is not so high, due to the tow-axis rotational motion of spindle.

AMM024

The type-3 has intermediate characteristics of both the type-1 and type-2.

The kinematic motion deviations of three types of 5-axis machining centers are formulated as shown in the following equations. Equation (10) is for type-1, Eq. (11) for type-2 and Eq. (12) for type-3.

$$\mathbf{X}_W = \mathbf{A}^3(d_1)\mathbf{A}^6(\theta)\mathbf{A}^3(d_2)\mathbf{A}^4(\varphi)\mathbf{A}^3(d_3) \mathbf{A}^1(x)\mathbf{A}^3(d_4)\mathbf{A}^2(y)\mathbf{A}^3(d_5)\mathbf{A}^3(z)\mathbf{X}_T \quad (10)$$

$$\mathbf{X}_W = \mathbf{A}^3(d_1)\mathbf{A}^1(x)\mathbf{A}^3(d_2)\mathbf{A}^2(y)\mathbf{A}^3(d_3) \mathbf{A}^3(z)\mathbf{A}^6(\theta)\mathbf{A}^3(d_4)\mathbf{A}^4(\varphi)\mathbf{A}^3(d_5)\mathbf{X}_T \quad (11)$$

$$\mathbf{X}_W = \mathbf{A}^3(d_1)\mathbf{A}^6(\theta)\mathbf{A}^3(d_2)\mathbf{A}^1(x)\mathbf{A}^3(d_3) \mathbf{A}^2(y)\mathbf{A}^3(d_4)\mathbf{A}^3(z)\mathbf{A}^4(\varphi)\mathbf{A}^3(d_5)\mathbf{X}_T \quad (12)$$

where,

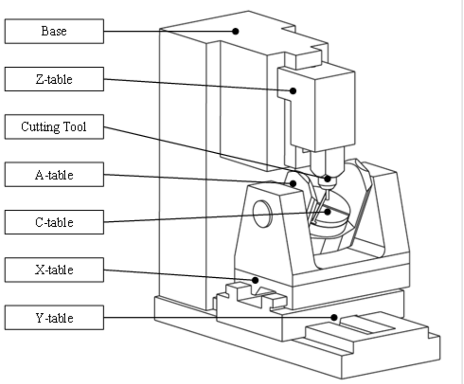
$\mathbf{X}_W$: Positions of workpieces

$\mathbf{X}_T$: Positions of tools

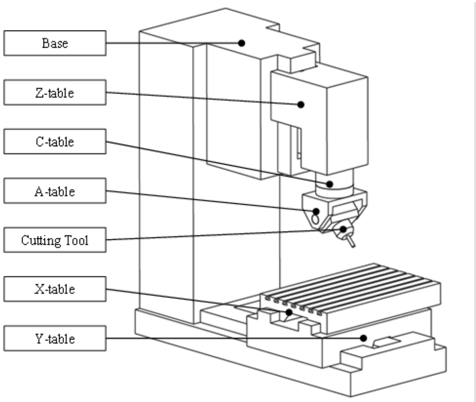
$\mathbf{A}^2(y)$: Y-axis linear motion

$\mathbf{A}^3(z)$: Z-axis linear motion

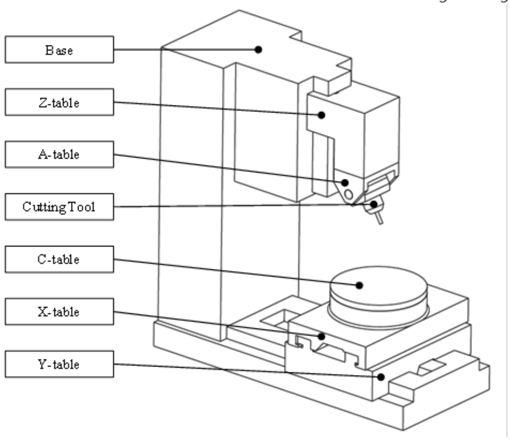
$\mathbf{A}^3(d_i)$: Translation between the tables (i=1~5)



(a) Type-1



(b) Type-2



(c) Type-3

Fig. 5 Model of 5-axis machining centers

4. Tolerance Design

It is very important to design a suitable set of tolerance values of machine products from the viewpoint of the both the product quality and the production costs[10, 11]. The tolerance design considered here means the design processes of the tolerance values of the guide-ways of the machining centers.

This research proposes a systematic design system for planning a suitable set of the geometric tolerances of the guide-ways considering trade-off between the requirements on the kinematic motion deviations and the ease of the manufacturing process. The design variables to be determined are the geometric tolerances t_i of individual guide-ways. 16 geometric tolerance values are considered for the 5-axis machine tools shown in Fig.5. The constraints considered here are the standard deviations of the kinematic motion deviations of the tools against the workpieces, which depend on the design parameters t_i. Followings summarize the procedures to estimate the standard deviations of kinematic motion deviations of machining centers based on the tolerance values t_i.

1. Apply the geometric tolerance t_i and calculate the standard deviations of the deviation parameters of the individual guide-ways by applying Eqs.(3) and (6).
2. Apply the deviations obtained in Step 1 to kinematic motion matrices given by Eqs.(10)-(12), and estimate the kinematic motion deviations of the tools against the workpieces of machining centers. Equation (13) shows the root-sum-square values of the standard deviations in 3-dimensional space of the kinematic motion deviations.

$$f(t_i) = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (13)$$

where,

σ_i : Standard deviations in i-direction of tools against workpieces (i=x, y, z)

Allowable values of the standard deviations are considered to be the design objective of the machine

AMM024

tools. Therefore, the constraints are represented by the following equation.

$$f(t_i) \le f_{tgt} \tag{14}$$

where,

f_{tgt} : Allowable standard deviations

4.1 Objective Function

Generally, the tolerance values are set smaller and smaller, the manufacturing processes of the guide-ways become more difficult. It is considered that the suitable tolerance value is should be designed based on the dimension of features. Fig.6 shows the relations between basic dimensions and tolerance values in ISO definitions in the tolerance. This relation can be approximated by applying the least-squares method, and represented as $t = ar^{0.34}$. This formula is considered to represent the relation of basic dimensions and tolerance values including the difficulty of manufacturing process. Then, objective function for this research is set to be Eq. (15), based on ISO Tolerance. Threshold values t_{imax} are also set to represent upper-limits of the tolerance values, in order to select a suitable set of the tolerance values considering the balance among all the tolerance values. t_{imax} are set, as shown in Table 1, based on JIS (Japan Industrial Standard) which is based in ISO.

$$g = \sum_{i=1}^{16} g(t_i) \tag{15}$$

where,

$$\begin{cases} g(t_i) = \dfrac{r_i^{0.34}}{t_i}, & (0 < t_i \le t_{i\,\max}) \\ g(t_i) = \dfrac{r_i^{0.34}}{t_{i\,\max}}, & (t_{i\,\max} < t_i) \end{cases}$$

Table1 Threshold value of general tolerances

Design Variables t_{imax}[mm]	Threshold value of general tolerances t_{imax}[mm]		
	Type1	Type2	Type3
t_1	0.2	0.2	0.1
t_2	0.2	0.2	0.3
t_3	0.3	0.1	0.1
t_4	0.2	0.1	0.1
t_5	0.3		
t_6			
t_7			
t_8			
t_9	0.3		
t_{10}			
t_{11}			
t_{12}			
t_{13}	0.2		
t_{14}			
t_{15}			
t_{16}			

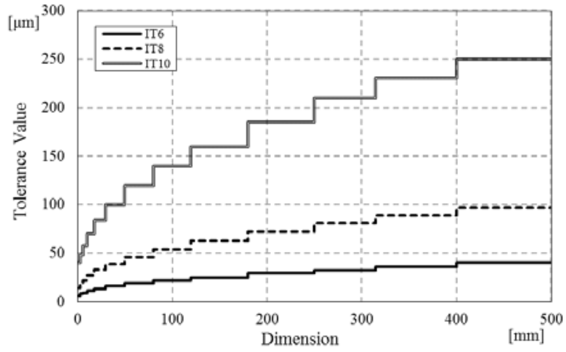


Fig.6 Relations between tolerance value and dimension of features

5. Case Study

The proposed method is applied to the tolerance design of three types of machining centers in Fig. 5 by setting the allowable kinematic deviation to 0.05mm. Figure 7 shows the optimum solutions.

The designed tolerances of t_3, t_5, t_7, t_9 , t_{11}, t_{15}, are smaller than other tolerance values, as shown in Fig.7. This means that the tolerance values of those guide-ways are rather important to reduce the standard deviations of the kinematic motion deviations between the tools and the work-pieces.

Figure 8 shows the values of objective function estimated by applying the designed tolerance values, respectively. The tolerances become smaller, the values of objective function become higher. This tendency coincide with the purpose to ease the manufacturing process by making the tolerance values smaller.

As shown in the Fig.8, the objective function values of the individual guide-ways are so different, due to that only the sum of the objective function values are evaluated by Eq. 15. Therefore, some mechanism is required, in the future research tasks, to reduce the distributions of the objective function values of the individual guide-ways.

6. Conclusion

Theoretical method is proposed to design the geometric tolerances of the guide-ways connecting the components of 5-axis machining centers, based on allowance of the kinematic motion deviation of the tools against the workpieces. This method is to design tolerances under the constraints on the standard deviations of shape generation functions of the tools against the workpieces.

The objective function is focused on the difficulties in the manufacturing processes of the guide-ways. The objective function is set to represent the trade-off between the kinematic motion deviation and the difficulty in the manufacturing processes based on ISO tolerance.

7. References

[1] Sugimura, N., Iwata, K., and Oba, F., Formation of shape generation processes of machine tools, Proc. of IFAC' 81, Vol. XIV (1981), pp.158-163.

[2] Reshetov, D. N., and Portman, V. T., 1988, Accuracy of machine tools," APME Press (1998).

[3] Sakamoto, S. and Inasaki, I., Error analysis of precision machine tools, Proc. of the 3rd Int. Conf. of Ultraprecision in Manufacturing Engineering (1994), pp.245-250.

[4] Sugimura, N. and Mitani, S., Analytical approach for design of alignment errors of machine tools, Proc. of 1998 Pacific Conference on Manufacturing (1998), pp.371-374.

[5] Yoshida, A., Sugimura, N., Takahashi, A., Thasana, W., Tanimizu, Y. and Iwamura, K., A Study on Tolerance Design for Kinematic Motion Deviations of Machining Centers Based on Geometric Tolerances , paper presented in *the 5th TSME-ICoME(2014)*, CD-ROM, Chiang Mai, Tailand.

[6] Satonaka, N., Sugimura, N., Tanimizu, Y., Iwamura, K., Analysis of kinematic motion deviations of machining centers based on geometric tolerances, Proc. of the 4th LEM-21 (2007), pp.629-634.

[7] Satonaka, N., Sugimura, N., Tanimizu, Y., Iwamura, A study on modeling and analysis of kinematic motion deviations of machine tools (2nd Report, Modeling and analysis of linear tables and machine tools, Trans. JSME, 74, 737 (2008), pp.198-205. (in Japanese)

[8] Sugimura, N., Nakamoto, K. and Satonaka, N., A study on statistical analysis of geometric tolerances of products," Proc. of the 17th International conference on Production Research (2003), CD-ROM, pp.1-6.

[9] Sugimura, N., Watabiki, H., Thasana, W., Iwamura, K., and Tanimizu, Y., Analysis of Kinematic Motion Deviations of Rotary Tables Based on Geometric Tolerances. J. of Advanced Mechanical Design, Systems, and Manufacturing, 6, 7, 1132-1142 (2012).

[10] Takazawa, K., Design of Parts Accuracy and Cost Performance, JSPE, 48-4, April 1982, pp.423-428(in Japanese)

[11] YOSHIMOTO, I., Accuracy-Precision Design in a Restricted Sense, Trans. JSME, 84-749, April 1981, pp.371-375(in Japanese)

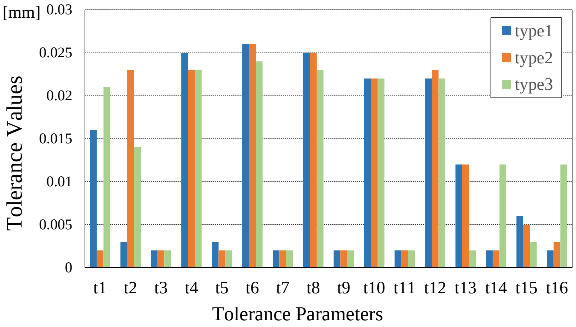


Fig7. Tolerance values of individual guide-ways

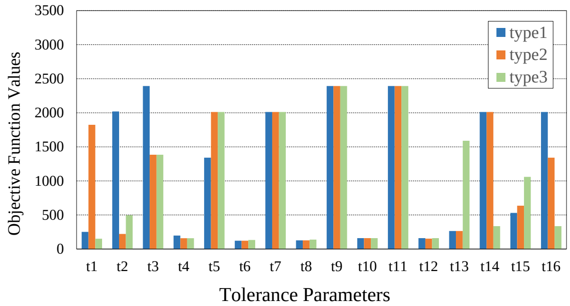


Fig8. Objective function values of individual guide-ways