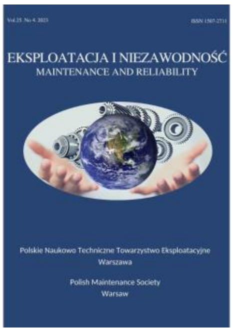

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Process machining allowance for reliability analysis of mechanical parts based on hidden quality loss

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Highlights

- Machining allowance is concerned to predict part's reliability.
- The machining allowance tolerance is used as the process capability criterion.
- Part failure quantity prediction model based on hidden quality loss function is improved.
- The process allowance-reliability prediction model is deduced based on hidden quality loss function.
- The model is applicable to the reliability prediction of machining allowance under normal distribution.

Abstract

The machining allowance variation is significant for the reliability of a part during the machining process. Usually, when the machining allowance of a part increases, the machining and production cost also increase. When the machining allowance decreases, the machining surface will have defects. The parts will produce many scraps and reliability will decrease. The machining allowance of a part consists of multiple process machining allowances. To analyze the impact caused by machining allowance variation, the hidden quality loss and process machining allowance are combined through the process capability index (PCI). Then the asymmetric quadratic quality loss function (AQF) and quadratic exponential function (QEF) are used to analyze them. A prediction model of hidden quality loss of process machining allowance is proposed. On the premise that the quality characteristic value obeys normal function distribution, a numerical model is given and used to obtain process machining allowance-inherent reliability of the product. The actual case is used to compare and verify the two models.

Keywords

reliability analysis, Process machining allowance, hidden quality loss, process capability index.

1. Introduction

During machining, a part often has multiple stages of manufacturing involving different machining methods. Variations in the machining process may cause defects on the part. Machining allowance means the designer must remove some material from the part's surface or part blank. The purpose of machining allowances is to remove defects left by the previous process and ensure quality consistency14. In the actual processing of parts, as the machining allowance of the part increases, it is necessary to control and monitor the machine tool processing1317183738. The production cost will also increase. However, when reducing the machining allowance, the part will have certain machining defects, and the quality will not be satisfactory. These defects may be subject to random fracture in the subsequent process19. In order to assess the quality of a manufactured product, Wu et al.34 proposed a multi-level optimization model for allocating machining allowances. This model is associated with machining defects based on the risk. Increasing the machining allowance may result in the deformation of the part11163536. Liu et al.1520 proposed an automatic determination model for machining allowances by

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analyzing factors that affect it. With the development of technology, new methods are available for analyzing machining allowances89. Besides, some studies on manufacturing cost planning and quality issues associated with the machining process can reduce time and cost101227.

Process capability refers to the ability of a process to achieve a specific level of processing quality under normal quality fluctuations. It is generally accepted that both machining accuracy and part qualification rates are determined by process capability33. A product's manufacturing quality primarily depends on the level of process capability. Technical requirements for a product often dictate the desired level of manufacturing quality. Designers introduce a process capability index to establish a link between process capability and technical requirements24.

The dimensional tolerances of each part in the machining process can affect the final manufacturing cost and the product quality2. A narrow tolerance requires a complex and costly manufacturing process, while a broad tolerance can compromise product quality28. Machining allowance is especially significant among the various factors that influence dimensional tolerances. Hence, it is necessary to consider manufacturing costs and quality losses when evaluating the impact of machining allowances. This effect can be investigated using the quality loss function29. Taguchi proposes a quadratic mass loss function31 that enhances the traditional view of quality loss. A function is suggested that considers the quality characteristic values within the tolerance range when they follow a normal distribution1252630. The function is extended in the following research7. However, these researchers ignore the rate of change of quality loss when the quality characteristic values deviate from the design target values. Mao et al.323 construct a quadratic exponential mass loss function to address this issue. The hidden quality cost is also introduced, which refers to the quality loss of qualified products caused by variations in quality characteristic values and processes.

Reliability is a quality indicator of a product. It depends on the product design and production process, which are determined by the design and production level. This is called inherent reliability. The reliability of mechanical parts ensures economic efficiency, service life, and quality stability. To predict and evaluate the product reliability during service and improve the quality reliability, Chen et al.45 propose a reliability assignment method for multi-attribute uncertain preferences. Luo et al.22 suggest that dimensional and tolerance variations of parts affect reliability. Mao et al.23 propose a reliability prediction model considering hidden quality loss and process capability index. Chuang et al.6 propose a reliability maintenance strategy during the repair period.

Previous authors have mainly studied the machining allowance analysis of machining efficiency, cost, part deformation, and fracture. They have also combined the process capability index and part quality. Some have used the quality loss function to relate the part tolerance to the final manufacturing cost. Then, they used reliability to analyze the product quality based on the quality loss function. However, few have established a link between the process allowance of a part and its reliability. This paper is organized as follows. Section 2 discusses the factors influencing machining allowance and its model selection. Section 3 derives a reliability prediction model based on the AQF and QEF for process machining allowance-hidden quality loss when the quality characteristic values follow a normal distribution. The derivation also incorporates the process capability index. Section 4 presents a case study to analyze how the process machining allowance affects the product reliability. It also compares the range of two reliability model choices. Section 5 concludes the paper.

2. Analysis of machining allowance and its influencing factors

The machining allowance is the amount of material that needs to be removed from a part in machining. It is allocated to each machining process according to the process machining allowances Z_i for each process.

In machining processes, it is generally assumed that the initial dimensional value of the part or part blank is located at the center of the tolerance specification. As shown in Fig. 1, the machining allowance for a given process is defined as the difference in process dimensions between two consecutive processes15. In other words, the machining allowance of a process Z_i is the difference between the dimension of this process A_i and the dimension of the previous process A_{i-1}.

Given that tolerances influence process dimensions, the maximum machining allowance $Z_{i\max}$ and the minimum machining allowance $Z_{i\min}$ are established. In practical applications, the minimum machining allowance represents the lower threshold that must be maintained to ensure satisfactory machining quality.

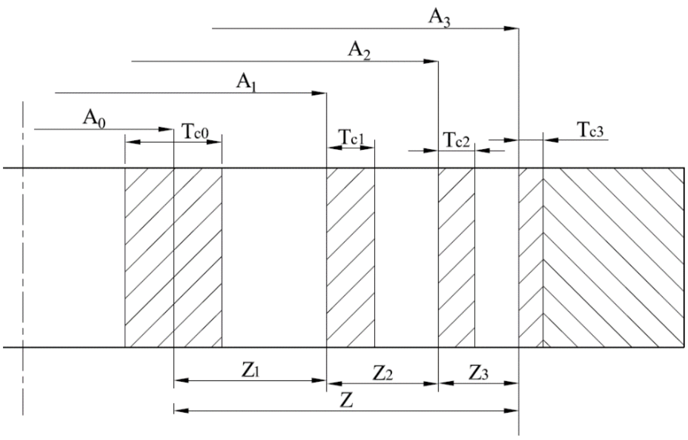

Fig. 1. Diagram of machining allowance under multi-process of rotary surface.

In conjunction with the annotations depicted in Fig.1, the minimum machining allowance $Z_{i\min}$ is calculated as the difference between the minimum size of process $A_{i\min}$ and the maximum size of the preceding process $A_{(i-1)\max}$. The maximum size of the preceding process $A_{(i-1)\max}$ is determined by adding its dimensional tolerance $T_{c(i-1)}$ to its minimum size $A_{(i-1)\min}$, as expressed in the following equation:

$$Z_{i\min} = \left|A_{i\min} - A_{(i-1)\max}\right| = A_i - A_{i-1} - T_{c(i-1)} \tag{1}$$

The maximum machining allowance $Z_{i\max}$ is calculated as the difference between the maximum size of process $A_{i_{\max}}$ and the minimum size of the preceding process $A_{(i-1)\min}$. The maximum size of process $A_{i_{\max}}$ is determined by adding its dimensional tolerance T_{ci} to its minimum size $A_{i\min}$, as expressed in the following equation:

$$Z_{i\max} = \left|A_{i_{\max}} - A_{(i-1)\min}\right| = A_i - A_{i-1} + T_{ci} \tag{2}$$

The machining allowance tolerance T_{Zi} is defined as the difference between the maximum value of the machining allowance $Z_{i\max}$ and its minimum value $Z_{i\min}$. By applying Equations (1) and (2), the equation for calculating the machining allowance tolerance can be derived as follows:

$$T_{Zi} = Z_{i\max} - Z_{i\min} = T_{ci} + T_{c(i-1)} \tag{3}$$

As shown in Fig.1, the initial dimension is positioned at the midpoint of the tolerance specification. The equation for computing the total machining allowance is presented below:

$$Z = \sum_{i=1}^{n} Z_{imin} + \sum_{i=1}^{n-1} T_{ci} + \frac{T_{c0}}{2} \tag{4}$$

where Z_i is the machining allowance for process i, T_{c0} is the initial dimensional tolerance, T_{ci} is the dimensional tolerance for process i, A_i is the dimension for process i, n is the total number of machining processes, and i is the work sequence number, $i = 1,2,\cdots,n$.

The Equation (4) shows that the total machining allowance Z is determined by the minimum machining allowance $Z_{i\min}$ and dimensional tolerance T_{ci} of each process.

Several factors, including surface defects and roughness of the part or part blank being machined, dimensional tolerances during machining, positional deviations, and clamping errors are known to impact the machining allowance significantly. A study of the primary factors affecting the machining allowance has led to the proposal of requirements for the minimum machining allowance of the process15. However, these requirements alone are insufficient for use as target values for the process machining allowance. Consequently, this study adopts the process machining allowance model proposed by Liu et al.20, which posits that the process machining allowance comprises three major components: the machining accuracy of the preceding process, surface quality and installation error of this process. These factors can be further subdivided into eight specific items: machining accuracy, roughness, depth of the defect layer on the surface to be machined in the preceding process, size and positional tolerance of the surface to be machined in the current process, positioning error, clamping error and error of fixture elements in the current process. As a result, machining allowance models suitable for flat and rotary surfaces have been proposed. The corresponding equations are presented as Equation (5) and Equation (6), respectively.

$$Z_i = K_L\varepsilon_L + \varepsilon_F + \varepsilon_C + 0.001Ra_{(i-1)} + I_{s(i-1)} + \sqrt{T_{c(i-1)}^2 + T_{p(i-1)}^2} \tag{5}$$

$$Z_i = K_L\varepsilon_L + \varepsilon_F + \varepsilon_C + 0.002Ra_{(i-1)} + 2I_{s(i-1)} + \sqrt{T_{c(i-1)}^2 + T_{p(i-1)}^2} \tag{6}$$

Rotary surfaces serve as the primary focus of this study, although flat machining types can also be analyzed using this method. The errors ε_L, ε_F, and ε_C are typically caused by clamping and can be combined into a single error term ε_i to represent clamping error. While ε_i is subject to human and machine influence, for this analysis, it is assumed that these objective factors are negligible and set $\varepsilon_i = 0$. Under this assumption, Equation (6) simplifies to the following expression:

$$Z_i = 0.002Ra_{(i-1)} + 2I_{s(i-1)} + \sqrt{T_{c(i-1)}^2 + T_{p(i-1)}^2} \quad (7)$$

where $Ra_{(i-1)} = 0.1 \times 2^{J_{a(i-1)}-3}$, $I_{s(i-1)} = \frac{0.3}{16-J_{i-1}}$.

In the above equation, Z_i is the machining allowance for the process i (mm), K_L is the feature integrated dimensional parameter coefficients, ε_L is the positioning errors caused by inaccurate positioning surfaces, and non-coincidence of references for the process i (mm), ε_C is the clamping error for the process i (mm), $Ra_{(i-1)}$ is the surface roughness for the process $i-1$ (μm), $I_{s(i-1)}$ is the surface defect layer depth for the process $i-1$ (mm), $T_{c(i-1)}$ is the dimensional tolerance for the process $i-1$ (mm), $T_{p(i-1)}$ is the position tolerance for the process $i-1$ (mm), J_{i-1} is the feature accuracy grade for the process $i-1$, $J_{a(i-1)}$ is the surface roughness equivalent accuracy grade for the process $i-1$.

3. Reliability modeling based on hidden quality loss

Taguchi's view of quality31 suggests that even when a product falls within specification limits, variations in its quality characteristics can result in quality losses. In other words, even products that meet specifications can generate what is known as hidden quality loss. The hidden quality loss is used to establish a relationship between the two to examine the impact of process machining allowance on part reliability. When parts leaving the factory have tolerances wider than their design tolerances, manufacturers can rework them to bring them within specification limits. Conversely, when parts leaving the factory have tolerances narrower than their design tolerances, they must be scrapped and cannot be reworked into qualified products. These two scenarios result in an asymmetric quality loss function with respect to the target value. The AQF and QEF are used to conduct the relevant analysis. The dimensional tolerance of a part is linked to the process machining allowance tolerance through the use of PCI. By establishing a connection between process machining allowance and hidden quality loss, PCI enables us to estimate the hidden quality loss of qualified parts. Then, a reliability model is constructed using the hidden quality loss derived from these two functions. This allows us to relate process machining allowance to reliability.

It is assumed that the quality characteristics follow a normal distribution, denoted as $x \sim N(\mu, \sigma^2)$, where μ is the mean value of x, σ is its standard deviation. In actual manufacturing, x is the value of process machining allowance, μ is the mean of process machining allowance value, σ is the standard deviation of process machining allowance value. The normal distribution density function is given by $f_N(x)$, while the standard normal distribution density function and distribution function are represented by $\varphi(x)$ and $\Phi(x)$, respectively. The relevant equations are provided below:

$$f_N(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-\mu)^2}{2\sigma^2}} \quad (8)$$

$$\varphi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \quad (9)$$

$$\Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \mathrm{d}x \quad (10)$$

3.1. Derivation of formula based on the AQF

According to the Taguchi quality loss function, the AQF is as follows:

$$L_{AQF}(x) = \begin{cases} A_1 & x < D_L \\ k_1(x-D)^2 & D_L \le x < D \\ k_2(x-D)^2 & D \le x \le D_U \\ A_2 & x > D_U \end{cases} \quad (11)$$

where $L_{AQF}(x)$ is the loss of product quality per unit under the AQF, x is the value of product quality characteristic, D is the target value of quality characteristics, D_L is the lower limit of quality specification, D_U is the upper limit of quality specification, A_1 is the quality loss caused when below the lower limit of quality specification, A_2 is quality loss when the upper limit of the quality specification is exceeded, k_1, k_2 are the mass loss coefficients to the left and right of the target value, respectively.

$$k_1 = \frac{A_1}{(D-D_L)^2} \qquad k_2 = \frac{A_2}{(D_U-D)^2} \quad (12)$$

Estimation of expected quality cost $E\left(L_{AQF}(x)\right)$ based on Taguchi method and probability theory:

$$\begin{aligned} E(L_{AQF}(x)) &= \int_{-\infty}^{+\infty} L_{AQF}(x) f_N(x)\, dx \\ &= \int_{-\infty}^{D_L} L_{AQF}(x) f_N(x) \mathrm{d}x + \int_{D_U}^{+\infty} L_{AQF}(x) f_N(x) \mathrm{d}x + \int_{D_L}^{D_U} L_{AQF}(x) f_N(x)\, dx \end{aligned} \quad (13)$$

Let $C_{AQF} = \int_{D_L}^{D_U} L_{AQF}(x) f_N(x)\, dx$, then

$$C_{AQF} = \int_{D_L}^{D} k_1(x-D)^2 f_N(x)\,dx + \int_{D}^{D_U} k_2(x-D)^2 f_N(x)dx \tag{14}$$

C_{AQF} represents the average quality loss for a batch of products and includes quality losses from non-qualified products. To estimate the quality loss of a batch of qualified products, the quality loss from non-qualified products must be transferred to qualified products. Let C_{0AQF} denote the quality loss of a single qualified product, and let q represent the passing rate for a batch of products. The relevant equation is given below:

$$q = \int_{D_L}^{D_U} f_N(x)\mathrm{d}x = \int_{D_L}^{D_U} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \mathrm{d}x = \Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right) \tag{15}$$

Then the relationship between C_{0AQF} and C_{AQF} is as follows:

$$C_{0AQF} = \frac{1}{q} C_{AQF} \tag{16}$$

Substituting Equation (14) into (16), the equation for C_{0AQF} is given as follows：

$$\begin{aligned} C_{0AQF} = {} & \frac{k_1}{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)} \left\{ [\sigma^2 + (D-\mu)^2] \left[\Phi\left(\frac{D-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)\right] \right. \\ & \left. +\sigma(D-\mu)\varphi\left(\frac{D-\mu}{\sigma}\right) + \sigma(D_L-\mu)\varphi\left(\frac{D_L-\mu}{\sigma}\right) - 2\sigma(D-\mu)\varphi\left(\frac{D_L-\mu}{\sigma}\right) \right\} \\ & + \frac{k_2}{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)} \left\{ [\sigma^2 + (D-\mu)^2] \left[\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)\right] \right. \\ & \left. -\sigma(D-\mu)\varphi\left(\frac{D-\mu}{\sigma}\right) - \sigma(D_U-\mu)\varphi\left(\frac{D_L-\mu}{\sigma}\right) + 2\sigma(D-\mu)\varphi\left(\frac{D_U-\mu}{\sigma}\right) \right\} \end{aligned} \tag{17}$$

During the machining of parts, an excessively large machining allowance can increase the labor required, reduce productivity, and increase costs. Conversely, an excessively small machining allowance may increase the number of processes required and may not effectively eliminate errors and surface defects from previous processes, potentially resulting in scrap. Suppose assuming that the target value for machining allowance is at the center of the specification range (i.e., $D = \frac{D_U-D_L}{2}$ and $T_U = T_L = \Delta_T$) and that the process is unbiased (i.e., $\mu = D$). In that case, the equation for PCI can be expressed as follows:

$$C_p = \frac{D_U - D_L}{6\sigma} = \frac{D + T_U - (D - T_L)}{6\sigma} = \frac{T_U + T_L}{6\sigma} = \frac{T_Z}{6\sigma} \tag{18}$$

Then the PCI equation can also be expressed by the following equation:

$$C_p = \frac{D_U - D_L}{6\sigma} = \frac{T_Z}{6\sigma} = \frac{\Delta_T}{3\sigma} \tag{19}$$

where T_U is the upper deviation of machining allowance target value D, T_L is the lower deviation machining allowance target value D , T_Z is the value of machining allowance tolerance and Δ_T is half of the tolerance range.

Equation (19) describes the ability to meet the specified machining allowance tolerance when producing a particular part. Under normal distribution, 99.73% of products fall within the interval $[\mu - 3\sigma, \mu + 3\sigma]$. The ratio of the design machining tolerance T_Z to 6σ is used to gauge the extent to which process capability meets technical requirements. As the standard deviation of machining allowance σ decreases, machining accuracy improves, and machining stability and process capability indicators become stronger. From Equations (18) and (19), the following expressions are derived:

$$\Delta_T = 3\sigma C_p \tag{20}$$

$$D_U - \mu = D + T_U - \mu = \Delta_T = 3\sigma C_p \tag{21}$$

$$D_L - \mu = D - T_L - \mu = -\Delta_T = -3\sigma C_p \tag{22}$$

Substitute Equations (20), (21), and (22) into (17), then the following equation is given:

$$C_{0AQF} = (A_1 + A_2) \frac{\Phi(3C_p) - 3C_p\varphi(3C_p) - \frac{1}{2}}{9{C_p}^2[2\Phi(3C_p) - 1]} \tag{23}$$

Substitute Equation (18) into (23), then the following equation is given:

$$C_{0AQF} = (A_1 + A_2) \frac{\Phi\left(\frac{T_Z}{2\sigma}\right) - \frac{T_Z}{2\sigma}\varphi\left(\frac{T_Z}{2\sigma}\right) - \frac{1}{2}}{\left(\frac{T_Z}{2\sigma}\right)^2 \left[2\Phi\left(\frac{T_Z}{2\sigma}\right) - 1\right]} \tag{24}$$

Let $\lambda = \frac{T_Z}{2\sigma}$. From Equation (3), we can derive that $T_{Zi} = T_{ci} + T_{c(i-1)}$, which leads to $\lambda = \frac{T_{ci} + T_{c(i-1)}}{2\sigma}$. In the machining process, the final dimensions of the machined parts must meet the design requirements. This forms a dimensional chain where the sum of each process's dimensional tolerances equals the final part's dimensional tolerance. Therefore, there must be a relationship between the dimensional tolerance of the previous and the current process. It is assumed that the dimensional tolerance of this process is ω times that of the previous process, where $0 < \omega \leq 1$ based on experience. This means that $T_{ci} = \omega T_{c(i-1)}$. Thus, the following equation is given:

$$\lambda = \frac{T_{c(i-1)} + \omega T_{c(i-1)}}{2\sigma} = \frac{\omega + 1}{2\sigma} T_{c(i-1)} \tag{25}$$

Substitute Equation (7) into (25), the equation is as follows:

$$\lambda = \frac{\omega+1}{2\sigma}T_{c(i-1)} = \frac{\omega+1}{2\sigma}\sqrt{\left(Z_i - 0.002Ra_{(i-1)} - 2I_{s(i-1)}\right)^2 - T_{p(i-1)}^2} \quad (26)$$

The λ is defined as the machining allowance impact factor. From Equation (26), it is clear that when obtaining a large amount of machining allowance data, σ is the standard deviation of the data sample. In a machining process, $Ra_{(i-1)}$, $I_{s(i-1)}$, $T_{p(i-1)}$ are the known objective design parameters and Z_i is the variable machining allowance. Then λ is a function of Z_i. Equation (24) can be deformed as follows:

$$C_{0AQF} = (A_1 + A_2)\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \quad (27)$$

At this point, the hidden quality loss C_{0AQF} based on AQF is related to the machining allowance impact factor λ, which is influenced by the machining allowance of the process Z_i.

It is assumed that the number of parts in a batch is M, then the total hidden quality loss of the batch is C_0M. By transferring the hidden quality loss of all parts to the parts that cause larger quality loss, the number of simulated failures in a batch of qualified parts m_s can be obtained as follows:

$$m_s = \frac{C_0M}{A} \quad (28)$$

This model ignores that when A reaches its maximum value, the number of failures is at its minimum. Manufacturers often opt for machine products with wider tolerances to reduce loss A_2 through reworking and repairing. However, when products are shipped with tolerances narrower than the design tolerances, they are often scrapped, resulting in a significant amount of unrepaired loss A_1. To accurately predict the number of simulated failure products in a batch of qualified products, it is necessary to attribute the implicit quality loss of each product to the product responsible for causing the quality loss. By letting $A = \alpha A_1 + \beta A_2$, Equation (28) can be rewritten as follows:

$$m_s = \frac{C_0M}{\alpha A_1 + \beta A_2} \quad (29)$$

where α and β are the weights of the two quality losses.

Referring to the inherent product reliability model proposed by Liu et al.23, the following equation is given:

$$R(t) = 1 - F(t) = \frac{N - n(t)}{N} \quad (30)$$

where $R(t)$ is the inherent product reliability, $F(t)$ is the failure rate, $n(t)$ is the number of product failures.

Substitute Equation (29) into (30), the equation is as follows:

$$R_I = \frac{M - m_s}{M} = 1 - \frac{C_0}{\alpha A_1 + \beta A_2} \quad (31)$$

Substitute Equation (27) into (31), the equation is as follows:

$$R_{IAQF} = 1 - \frac{A_1 + A_2}{\alpha A_1 + \beta A_2}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \quad (32)$$

At this point, the inherent reliability of the part R_{IAQF} is related to the machining allowance impact factor λ, which is influenced by the machining allowance of the process Z_i.

If $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, and $\beta = 0.1$, then the relationship between reliability R_{IAQF} and λ are shown in Fig. 2. As shown in Fig. 2, λ initially increases, and R_{IAQF} increases correspondingly. When λ reaches a specific value, λ is used as the denominator in the model and grows as a square. Besides, it also grows faster than the numerator, so the growth rate of R_{IAQF} become slow.

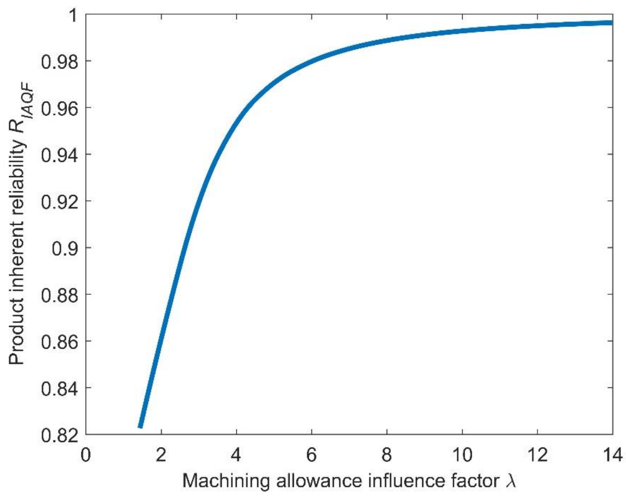

Fig. 2. The relationship between reliability R_{IAQF} and λ.

3.2. Derivation of formula based on the QEF

After machining is completed and the diameter of the shaft deviates from the set target value, the growth rate of mass loss caused by a large or small diameter differs. For large diameters, the growth rate of mass loss gradually decreases and eventually levels off as the shaft wears down to the target value during subsequent use. In contrast, for small diameters, the growth rate of mass loss gradually increases until the product is eventually scrapped. Then the QEF considering the rate of change is proposed23, the equation is as follows:

$$L_{QEF}(x) = \begin{cases} A_1 & x < D_L \\ k_1(x-D)^2 & D_L \le x < D \\ k_2(1 - e^{-x+D}) & D \le x \le D_U \\ A_2 & x > D_U \end{cases} \quad (33)$$

Where $L_{QEF}(x)$ is the loss of product quality per unit under the QEF, the corresponding equations for k_1 and k_2 at this point are as follows:

$$k_1 = \frac{A_1}{(D_L - D)^2} \qquad k_2 = \frac{A_2}{1 - e^{-D_U + D}} \tag{34}$$

According to Equation (13), the following equation can be obtained based on QEF:

$$C_{QEF} = \int_{D_L}^{D} k_1 (x - D)^2 f_N(x)\, dx + \int_{D}^{D_U} k_2 (1 - e^{-x+D}) f_N(x)\, dx \tag{35}$$

Expressing Equation (16) in terms of C_{QEF}, the equation for C_{0QEF} is given:

$$\begin{aligned} C_{0QEF} &= \frac{C}{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)} \\ &= \frac{k_1}{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)}\left\{[\sigma^2 + (D-\mu)^2]\left[\Phi\left(\frac{D-\mu}{\sigma}\right) - \Phi\left(\frac{D_L-\mu}{\sigma}\right)\right]\right. \\ &\left. +\sigma(D-\mu)\varphi\left(\frac{D-\mu}{\sigma}\right) + \sigma(D_L-\mu)\varphi\left(\frac{D_L-\mu}{\sigma}\right) - 2\sigma(D-\mu)\varphi\left(\frac{D_L-\mu}{\sigma}\right)\right\} \\ &+ \frac{k_2}{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D-T_L-\mu}{\sigma}\right)}\left\{\Phi\left(\frac{D_U-\mu}{\sigma}\right) - \Phi\left(\frac{D-\mu}{\sigma}\right)\right. \\ &\left. -\frac{1}{2}e^{\left(D-\mu+\frac{\sigma^2}{2}\right)}\left[Erf\left(\frac{D_U-\mu+\sigma^2}{\sqrt{2}\sigma}\right) - Erf\left(\frac{D-\mu+\sigma^2}{\sqrt{2}\sigma}\right)\right]\right\} \end{aligned} \tag{36}$$

Substitute Equations (20), (21), and (22) into (36), then the following equation is given:

$$\begin{aligned} C_{0QEF} &= A_1 \frac{\Phi(3C_p) - 3C_p\varphi(3C_p) - \frac{1}{2}}{9C_p^2[2\Phi(3C_p) - 1]} \\ &+ A_2 \frac{\Phi(3C_p) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{3}{2}\sqrt{2}C_p + \frac{\sqrt{2}}{2}\sigma\right) - Erf\left(\frac{\sqrt{2}}{2}\sigma\right)\right] - \frac{1}{2}}{(1 - e^{-3\sigma C_p})[2\Phi(3C_p) - 1]} \end{aligned} \tag{37}$$

Substitute Equation (18) into (37), then the following equation is given:

$$\begin{aligned} C_{0QEF} &= A_1 \frac{\Phi\left(\frac{T_Z}{2\sigma}\right) - \frac{T_Z}{2\sigma}\varphi\left(\frac{T_Z}{2\sigma}\right) - \frac{1}{2}}{\left(\frac{T_Z}{2\sigma}\right)^2\left[2\Phi\left(\frac{T_Z}{2\sigma}\right) - 1\right]} \\ &+ A_2 \frac{\Phi\left(\frac{T_Z}{2\sigma}\right) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{1}{4}\sqrt{2}\frac{T_Z}{\sigma} + \frac{\sqrt{2}}{2}\sigma\right) - Erf\right.}{(1 - e^{-\frac{T_Z}{2}})\left[2\Phi\left(\frac{T_Z}{2\sigma}\right) - 1\right]} \end{aligned} \tag{38}$$

Let $\lambda = \frac{T_Z}{2\sigma}$. Equation (38) can be deformed as follows:

$$\begin{aligned} C_{0QEF} &= A_1 \frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \\ &+ A_2 \frac{\Phi(\lambda) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{\sqrt{2}}{2}\lambda + \frac{\sqrt{2}}{2}\sigma\right) - Erf\left(\frac{\sqrt{2}}{2}\sigma\right)\right] - \frac{1}{2}}{(1 - e^{-\sigma\lambda})[2\Phi(\lambda) - 1]} \end{aligned} \tag{39}$$

Similarly, the hidden quality loss C_{0QEF} based on QEF is related to the machining allowance impact factor λ, which is influenced by the process's machining allowance Z_i. Substituting Equation (39) into (31), the equation for R_{IQEF} under QEF is obtained as follows:

$$\begin{aligned} R_{IQEF} &= 1 - \frac{A_1}{\alpha A_1 + \beta A_2}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \\ &- \frac{A_2}{\alpha A_1 + \beta A_2}\frac{\Phi(\lambda) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{\sqrt{2}}{2}\lambda + \frac{\sqrt{2}}{2}\sigma\right) - Erf\left(\frac{\sqrt{2}}{2}\sigma\right)\right] - \frac{1}{2}}{(1 - e^{-\sigma\lambda})[2\Phi(\lambda) - 1]} \end{aligned} \tag{40}$$

Similarly, the inherent reliability of the part R_{IQEF} is related to the machining allowance impact factor λ, which is influenced by the machining allowance of the process Z_i.

If $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, and $\beta = 0.1$, then the relationship between reliability R_{IQEF} and λ is shown in Fig. 3. From Fig. 3, it can be obtained that as the machining allowance influence factor λ increases, σ decreases, i.e., the more robust the machining is, the more reliable it is. Compared to Fig. 2, this relationship is more consistent with actual production reliability predictions.

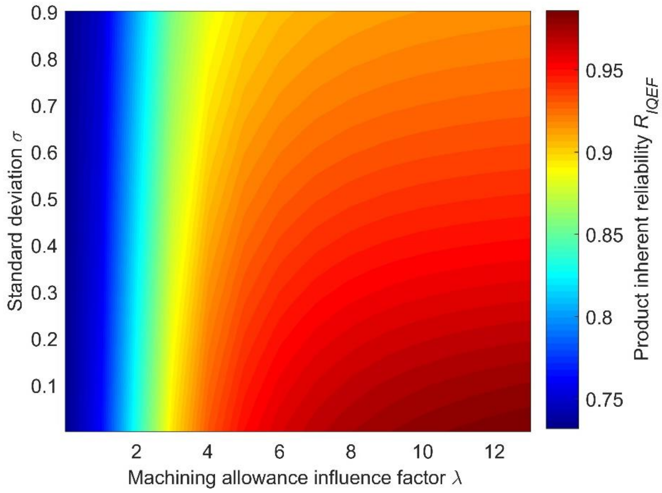

Fig. 3. The relationship between reliability R_{IQEF} and λ, standard deviation σ.

4. Results and discussion

As shown in Fig. 4, the long pin parts in a transparent high-temperature resistant theory teaching mold are used for reliability analysis of the process machining allowances. Pin parts are made of $35CrMnSiA$ hot rolled round steel. Its specification is $\phi 8.8mm \times 119mm$, as shown in Fig. 5 and 6. The dimensional tolerance is $\pm 0.40mm$, and the process route to be used is "Rough machining - Precision machining", as shown in Fig. 8.

Six specimens were selected, as shown in Fig. 4. The steps are as follows. In the first step, the outer dimensions of the raw material are measured at $30mm$, $60mm$ and $90mm$ from the end face with vernier calipers, as shown in Fig. 7. In the second step, the measurement results are sorted by specimen serial number as shown in Table 1. As shown in Table 1, the maximum and minimum values of the outside diameter of the six specimens meet the requirements of the part specifications.

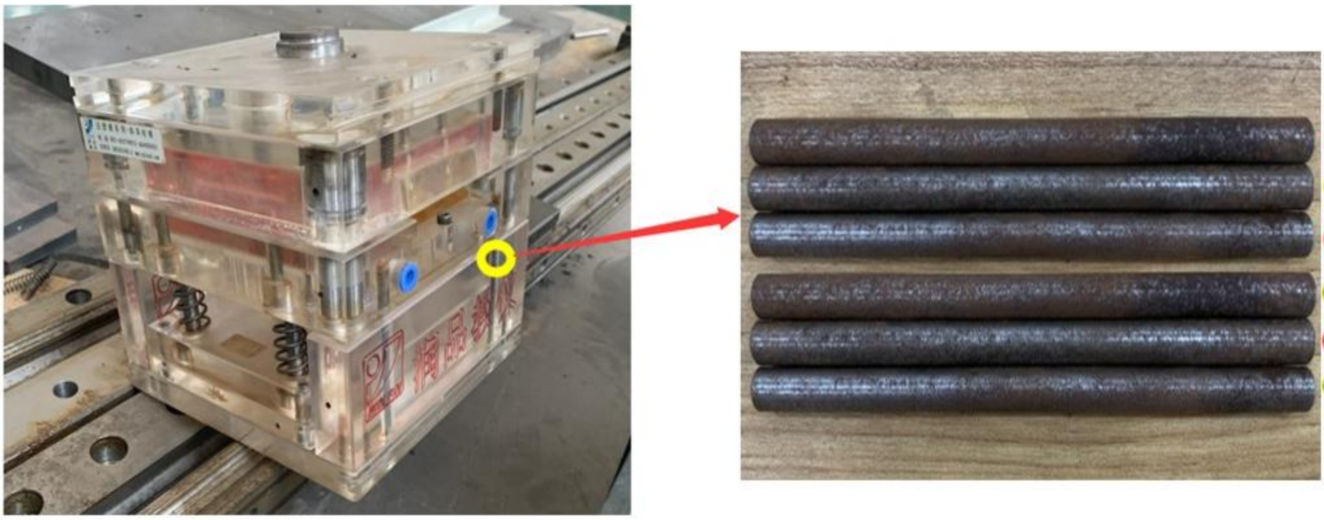

Fig. 4. Schematic diagram of six specimens from the mold.

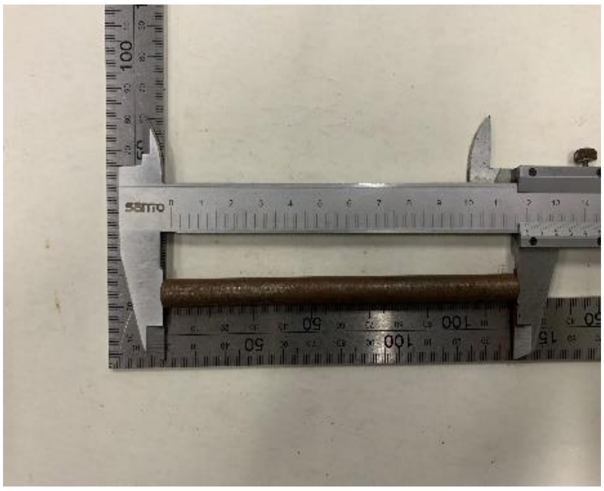

Fig.5. Length measurement of the pin part.

Fig. 6. Diameter measurement of the pin part.

a b c

Fig. 7. a, b, c is at $30mm$, $60mm$, and $90mm$ from the end face respectively

Table 1. Measurement results of pin diameter.

mm

Section position	Specimen No.1	Specimen No.2	Specimen No.3	Specimen No.4	Specimen No.5	Specimen No.6
Section A ($30mm$ from the end face)	8.84 8.80 8.76	9.00 8.84 8.94	9.00 8.82 8.62	8.92 8.70 8.80	8.80 9.00 8.42	8.84 8.82 8.76
Section A ($60mm$ from the end face)	8.82 8.88 8.82	8.76 8.80 8.82	8.72 8.66 9.12	8.74 8.84 8.72	8.62 8.68 8.58	8.78 8.80 8.78
Section A ($90mm$ from the end face)	8.78 8.80 8.86	8.90 8.96 9.14	8.78 9.00 8.80	8.86 8.88 9.00	8.94 8.90 8.84	8.82 8.80 8.78
μ	8.8178	8.9067	8.8356	8.8222	8.7533	8.7978

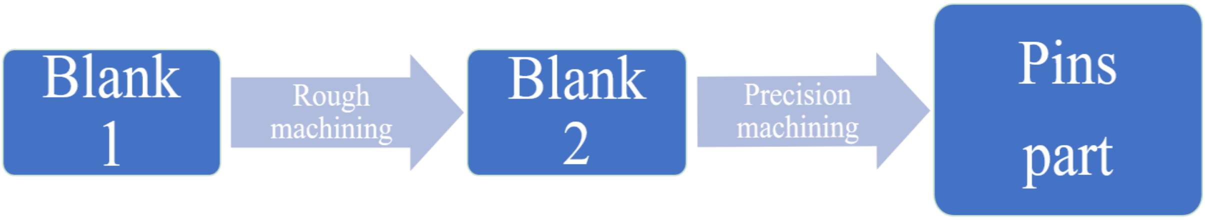

Fig. 8. Schematic diagram of pin parts machining.

The final dimensional tolerance of the part is $\pm 0.40mm$. To avoid the generation of false scrap, the equal tolerance method is used, then $\omega = 1$. In this case, there are two processes, so the dimensional tolerance before rough machining in the first process is $c0 = \pm 0.40mm$. The dimensional tolerance before precision machining in the second process is $c1 = \pm 0.40mm$. At the end of the second process, a pin part that meets the specifications with a dimensional tolerance of $c2 = \pm 0.40mm$.

The next step is the calculation of the parameters related to the two machining processes. Subsequently, the impact of process machining allowance on product reliability is analyzed and compared with the two methods developed above.

Calculation of relevant parameters during rough machining：

It is assumed that this processing adopts the grade processing method. The basic idea is to make the feature accuracy and surface roughness grade of this process three levels smaller than that of the previous process. For the roughing process, the roughing corresponding feature accuracy level is $J_1 = 12$, and the depth of the surface defect layer of the previous process is $I_{s0} = \frac{0.3}{16-J_0} = \frac{0.3}{16-(J_1+3)} = 0.3mm$. If the surface roughness equivalent accuracy class of blank 1 is 10, i.e., $J_{a0} = 10$, then the surface roughness of its previous process is $Ra_0 = 0.1 \times 2^{J_{a0}-3} = 0.1 \times 2^{10-3} = 12.8\mu m$. According to experience, in production, the position tolerance is generally often taken as 50% to 60% of the dimensional tolerance value21, in this case, it is taken $T_p = \frac{3}{5}T_c$. The dimensional tolerance value of blank 1 is $T_{c0} = 0.8mm$, then the position tolerance is $T_{p0} = \frac{3}{5}T_{c0} = 0.48mm$. The results of all parameters are collapsed into Table 2.

Table 2. Calculation results of relevant parameters during rough machining.

ω	$\varepsilon_1(mm)$	$Ra_0(\mu m)$	$I_{s0}(mm)$	$T_{c0}(mm)$	$T_{p0}(mm)$
1	0	12.8	0.3	0.8	0.48

Substitute the data from Table 2 into Equation (7), $Z_1 = 1.5586mm$. From Equation (3), it is obtained that $T_{Z1} = T_{c0} + T_{c1} = 0.8 + 0.8 = 1.6mm$. Since the target value is located at the center of the machining specification, the tolerance of Z_1 is $\pm 0.80mm$. The target value of the machining allowance of the first process is $2.3586mm$. The range of values of Z_1 is given as $1.5586mm \le Z_1 \le 3.1586mm$.

Substituting the data in Table 2 into Equation (26), it becomes the following equation:

$$\lambda = \frac{1+1}{2\sigma}\sqrt{(Z_1 - 0.002 \times 12.8 - 2 \times 0.3)^2 - 0.48^2} = \frac{\sqrt{(Z_1 - 0.6256)^2 - 0.2304}}{\sigma} \tag{41}$$

From Equation (41), it can be obtained that to make λ meaningful, i.e., The minimum machining allowance should be satisfied to remove the defects caused by the previous process. The Equation (41) is solved for $Z_1 > 1.1056$ or $Z_1 < 0.1456$. The above machining allowances meet the requirements. To facilitate the calculation and analysis, the value range of Z_1 is $1.56mm \sim 3.14mm$.

According to Equation (41), the value of λ is calculated concerning Z_1 and σ. The resulting graph is shown in Fig. 9. As can be observed from Fig. 9, λ increases as Z_1 increases and decreases as σ increases. The relationship between these variables is further illustrated in Fig. 10.

As shown in Fig. 10, the variables mentioned above exhibit a monotonic relationship. As the machining allowance Z_1 increases, so does the machining allowance impact factor λ. Conversely, as the standard deviation σ decreases (indicating better production robustness), λ also increases.

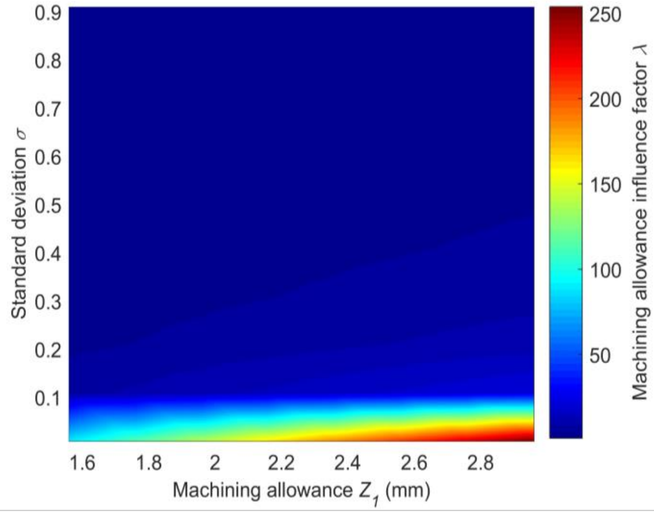

Fig.9. The relationship between λ and Z_1, σ.

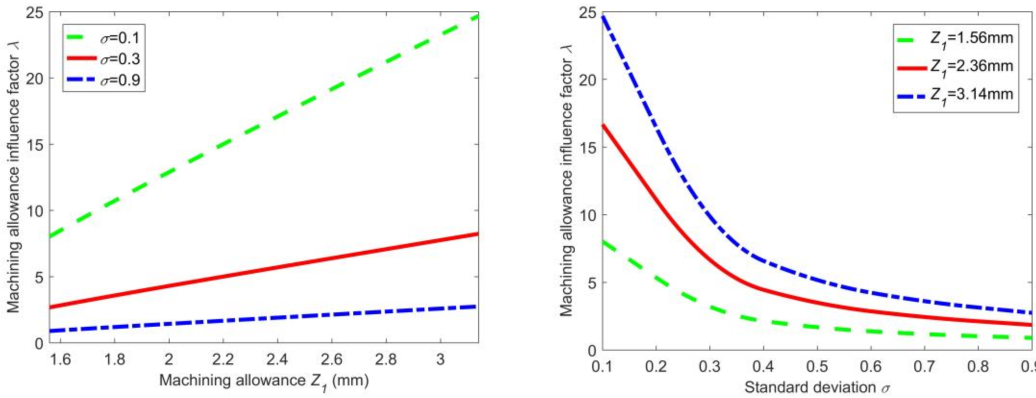

Fig. 10. The change law of λ under different Z_1 and σ.

According to Equation (32), (41), if $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, $\beta = 0.1$, The following equations are given:

$$R_{IAQF} = 1 - \frac{10}{7}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \tag{42}$$

where $\lambda = \frac{\sqrt{(Z_1 - 0.6256)^2 - 0.2304}}{\sigma}$

According to Equation (42), the variation of product inherent reliability $R_{I_{AQF}}$ with Z_1 and σ is shown in Fig. 11. Their relationship can be seen more clearly in Fig. 12. As shown in Fig. 12, the variables mentioned above exhibit a monotonic relationship. Specifically, as the machining allowance within the design range increases, so does the product reliability. Conversely, product reliability also improves as the standard deviation decreases (indicating better production robustness). As can be observed from the two-dimensional variation surface

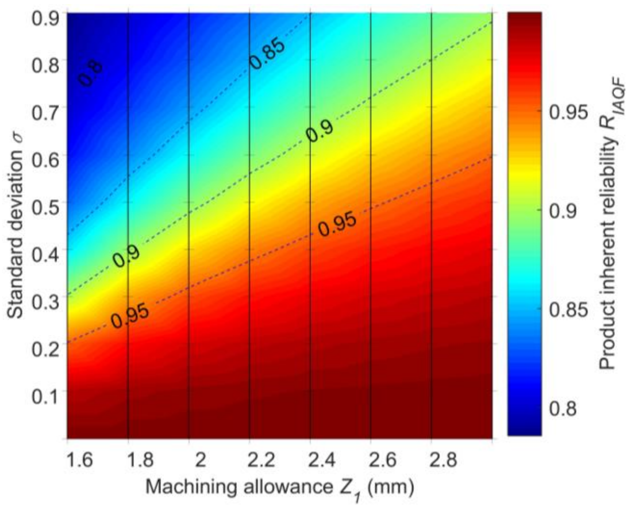

Fig. 11. The relationship between R_{IAQF} and Z_1, σ.

in Fig. 11, if it is stipulated that product reliability must satisfy a value of 0.9, there exists an optimal choice for values of Z_1

and σ. It also can be used to analyze the effect of the variation of machining allowance on the inherent reliability of the product.

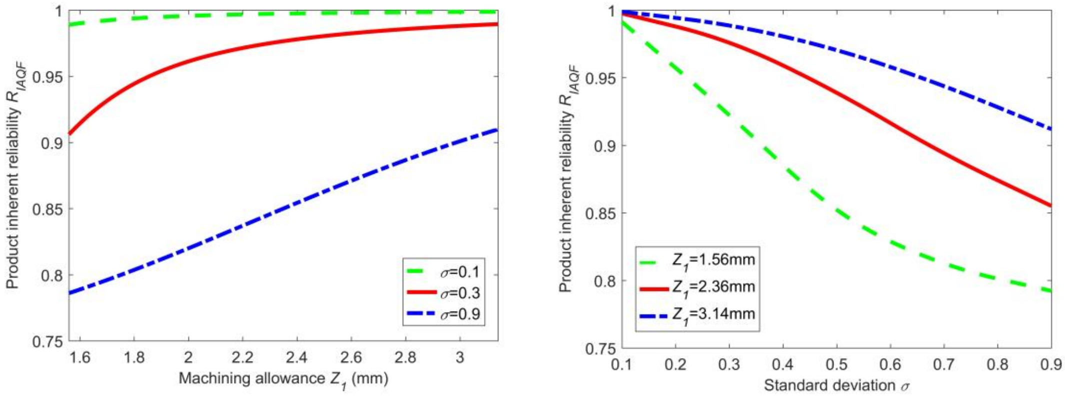

Fig. 12. The change law of R_{IAQF} under different Z_1 and σ.

According to Equation (40), (41), if $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, $\beta = 0.1$, The following equations are given:

$$R_{IQEF} = 1 - \frac{15}{14}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} - \frac{5}{14}\frac{\Phi(\lambda) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{\sqrt{2}}{2}\lambda + \frac{\sqrt{2}}{2}\sigma\right) - Erf\left(\frac{\sqrt{2}}{2}\sigma\right)\right] - \frac{1}{2}}{(1 - e^{-\sigma\lambda})[2\Phi(\lambda) - 1]} \tag{43}$$

where $\lambda = \frac{\sqrt{(Z_1 - 0.6256)^2 - 0.2304}}{\sigma}$

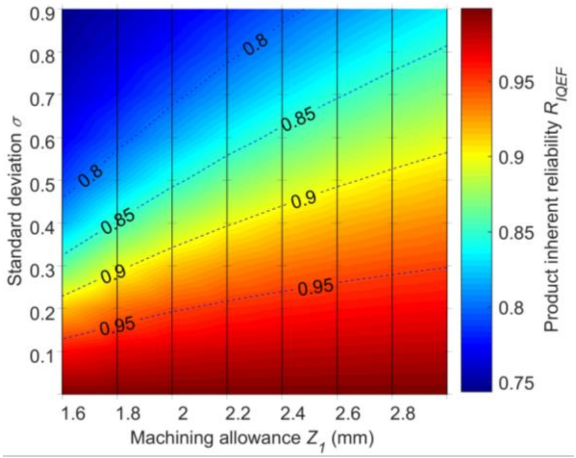

Fig. 13. The relationship between R_{IQEF} and Z_1, σ.

Equation (43) illustrates the variation of product inherent reliability R_{IQEF} concerning Z_1 and σ, as shown in Fig. 13.

The relationship between these variables is further elucidated in Fig. 14. As can be observed from the two-dimensional variation surface in Fig. 13, if product reliability is specified to meet a value of 0.9, the range of values for Z_1 and σ is reduced compared to that shown in Fig. 11. The reason for this range narrowing can be derived from Equation (31), which primarily depends on C_0. C_0 can be obtained through the derivation of AQF and QEF, respectively. As proposed earlier in this article, QEF is more accurate and better reflects production reality than AQF. It allows for a more precise analysis of the impact of changes in process allowance on the inherent reliability of the part.

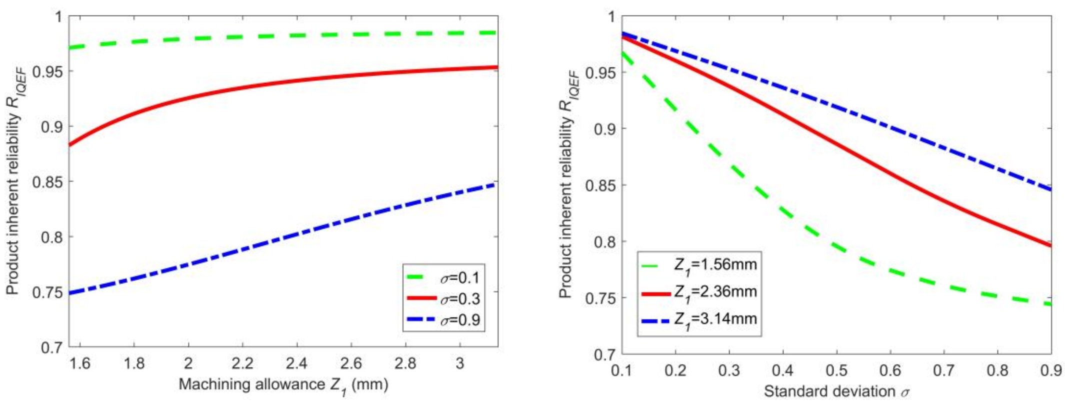

Fig. 14. The change law of R_{IQEF} under different Z_1 and σ.

Calculation of relevant parameters during precision machining:

For the second finishing process, the corresponding feature accuracy is $J_2 = 9$, then $I_{s1} = \frac{0.3}{16-J_1} = \frac{0.3}{16-12} = 0.075mm$. This processing adopts the grade treatment method, so the surface roughness grade of blank 2 is $J_{a1} = 7$, then the surface roughness is $Ra_1 = 0.1 \times 2^{J_{a1}-3} = 0.1 \times 2^{7-3} = 1.6\mu m$. The dimensional tolerance of blank 2 is $c1 = \pm 0.40mm$, then $T_{c1} = 0.8mm$, $T_{p1} = \frac{3}{5}T_{c1} = 0.48mm$. The obtained data are listed in Table 3.

Table 3. Calculation results of relevant parameters during precision machining.

ω	$\varepsilon_2(mm)$	$Ra_1(\mu m)$	$I_{s1}(mm)$	$T_{c1}(mm)$	$T_{p1}(mm)$
1	0	1.6	0.075	0.8	0.48

The machining allowance of the second process should ensure that the dimensional tolerances of the final part meet the requirements. It also removes the defects left by the rough machining of the blank 2. Substitute the data from Table 3 into Equation (7), $Z_2 = 1.0862mm$. From Equation (3), it is obtained that $T_{Z2} = 1.6mm$. Since the target value is located at the center of the machining specification, the tolerance of Z_2 is $\pm 0.80mm$. The target value of the machining allowance of the second process is $1.8862mm$. The range of values of Z_2 is given as $1.0862mm \le Z_2 \le 2.6862mm$.

Substituting the data in Table 3 into Equation (26), it becomes the following equation:

$$\begin{aligned}\lambda &= \frac{1+1}{2\sigma}\sqrt{(Z_2 - 0.002 \times 1.6 - 2 \times 0.075)^2 - 0.24^2} \\ &= \frac{\sqrt{(Z_2 - 0.1532)^2 - 0.2304}}{\sigma}\end{aligned} \tag{44}$$

From Equation (44), it can be obtained that to make λ meaningful, i.e., The minimum machining allowance should be satisfied to remove the defects caused by the previous process. The Equation (44) is solved for $Z_2 > 0.6332$ or $Z_2 < -0.3268$. The above machining allowances meet the requirements. To facilitate the calculation and analysis, the value range of Z_2 is $1.10mm \sim 2.68mm$.

According to Equation (44), the value of λ is calculated concerning Z_2 and σ. The resulting graph is shown in Fig. 15. As can be observed from Fig. 15, λ increases as Z_2 increases and decreases as σ increases. The relationship between these variables is further illustrated in Fig. 16.

A similar result as in Fig. 10 can be obtained in Fig. 16. As it is shown in Fig. 16, the variables mentioned above exhibit a monotonic relationship. As the machining allowance Z_2 increases, so does the machining allowance impact factor λ. Conversely, as the standard deviation σ decreases (indicating better production robustness), λ also increases.

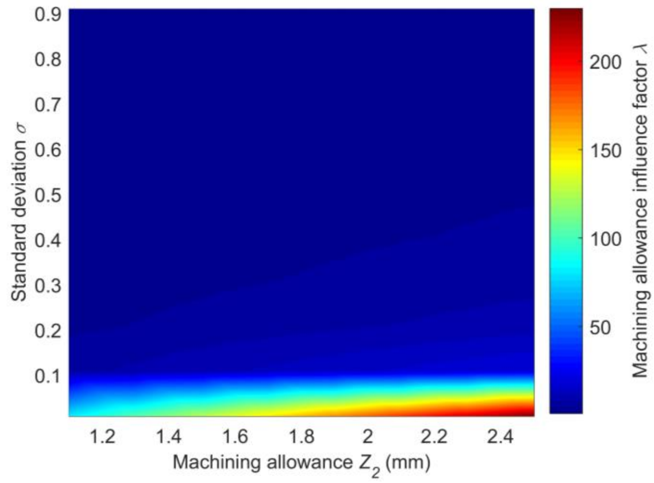

Fig. 15. The relationship between λ and Z_2, σ.

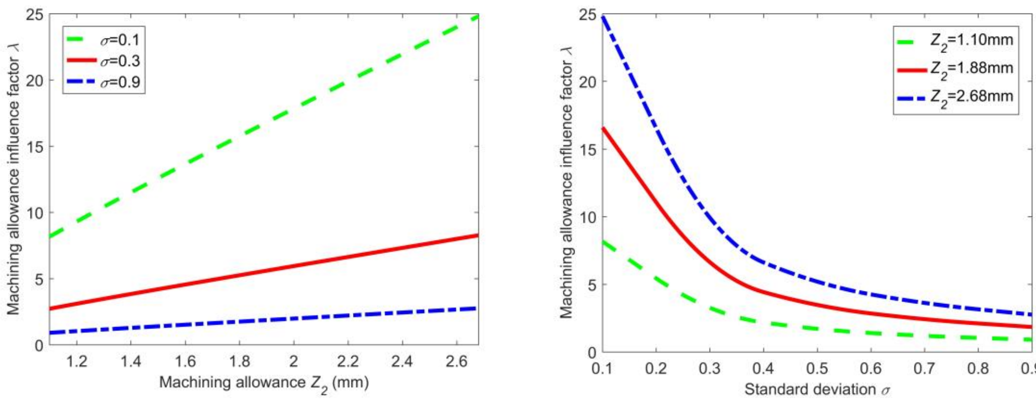

Fig. 16. The change law of λ under different Z_2 and σ.

According to Equation (32), (44), if $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, $\beta = 0.1$, The following equations are given:

$$R_{IAQF} = 1 - \frac{10}{7}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} \tag{45}$$

where $\lambda = \frac{\sqrt{(Z_2-0.1532)^2-0.2304}}{\sigma}$

According to Equation (45), the variation of product inherent reliability R_{IAQF} with Z_2 and σ is shown in Fig. 17. Their relationship can be seen more clearly in Fig. 18. A similar result to that shown in Fig. 12 can be obtained in Fig. 18. Comparing Fig. 18 with Fig. 12, it can be obtained that the rate of change of reliability concerning the process allowance and its standard deviation remains approximately the same in the finishing stage, despite the reduction of the machining allowance. This also serves to demonstrate the stability of the model to some extent. Comparing Fig. 17 with Fig. 11, it can be obtained that if the reliability is selected as 0.9, the range corresponding to the finishing stage is reduced compared to the roughing stage. This is following objective reality. As mentioned above, in the finishing stage, the machining allowance must not only be sufficient to remove defects from the previous stage, but also to ensure that the dimensions of the final produced part meet the design requirements. Consequently, the area must be reduced. It can also be used to examine the effect of variations in machining allowance on inherent product reliability.

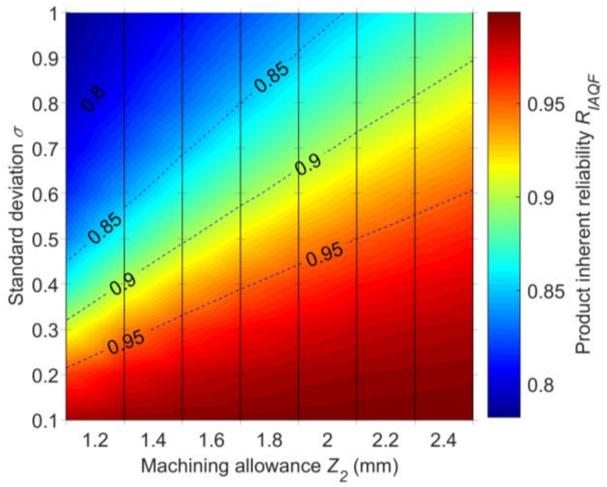

Fig. 17. The relationship between R_{IAQF} and Z_2, σ.

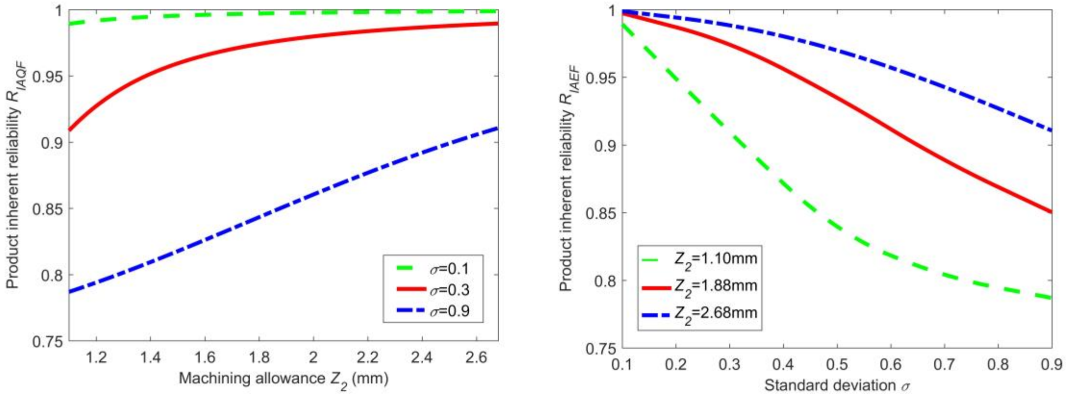

Fig. 18. The change law of R_{IAQF} under different Z_2 and σ.

According to Equation (40), (44), if $A_1 = 9$, $A_2 = 3$, $\alpha = 0.9$, $\beta = 0.1$, The following equations are given:

$$R_{IQEF} = 1 - \frac{15}{14}\frac{\Phi(\lambda) - \lambda\varphi(\lambda) - \frac{1}{2}}{\lambda^2[2\Phi(\lambda) - 1]} - \frac{5}{14}\frac{\Phi(\lambda) - \frac{1}{2}e^{\frac{\sigma^2}{2}}\left[Erf\left(\frac{\sqrt{2}}{2}\lambda + \frac{\sqrt{2}}{2}\sigma\right) - Erf\left(\frac{\sqrt{2}}{2}\sigma\right)\right] - \frac{1}{2}}{(1 - e^{-\sigma\lambda})[2\Phi(\lambda) - 1]} \quad (46)$$

where $\lambda = \frac{\sqrt{(Z_2-0.1532)^2-0.2304}}{\sigma}$

According to Equation (46), the variation of product inherent reliability R_{IQEF} with Z_2 and σ is shown in Fig. 19. Their relationship can be seen more clearly in Fig. 20. A similar result to that shown in Fig. 13 can be obtained in Fig. 19.

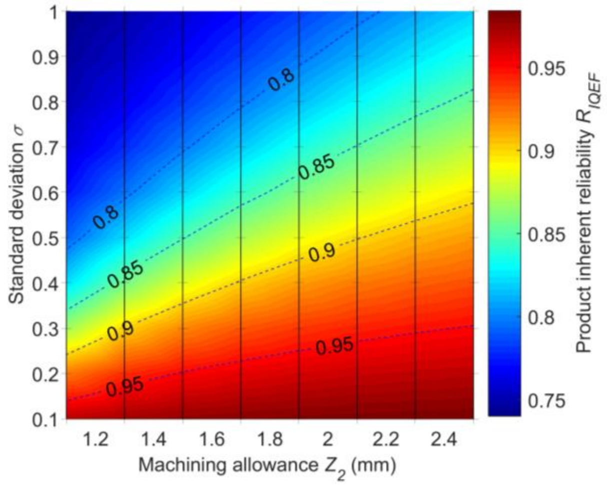

Fig. 19. The relationship between R_{IQEF} and Z_2, σ.

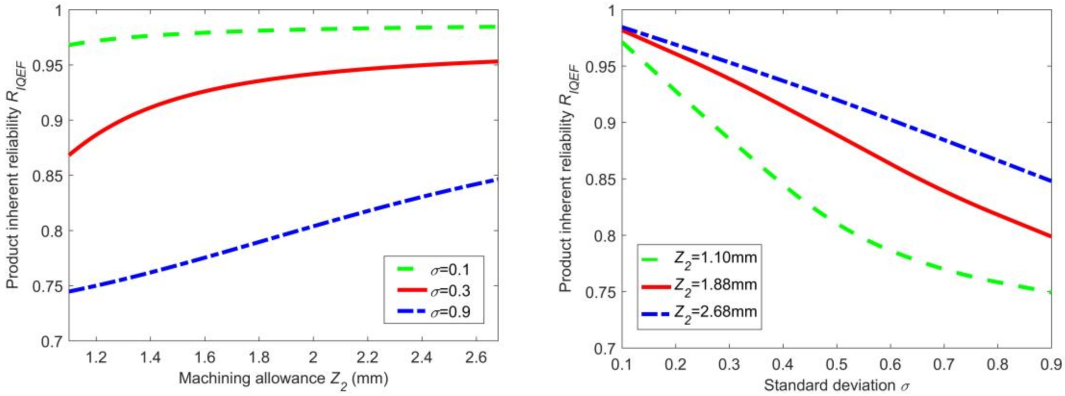

Fig. 20. The change law of R_{IQEF} under different Z_2 and σ.

The above analysis shows the stability as well as the applicability of the proposed model.

5. Conclusions

During the actual machining process of the part, different process machining allowances will lead to the changes of product reliability. Process machining allowance-reliability prediction methods are established based on AQF and QEF, respectively. Some consequences can be obtained.

1. During actual machining, excessive or minimal machining allowances can lead to changes of part dimensions and quality loss. In order to evaluate it, the product quality loss view is introduced, and AQF and QEF are adopted for comparison.

2. In order to use machining allowance tolerance as a benchmark to assess the level of machining quality for a given part, PCI is introduced to establish a relationship between process machining allowance and machining quality level.

3. It is assumed that quality characteristic values follow a normal distribution. Using the AQF and QEF, numerical models is generated to estimate the average hidden quality loss due to machining quality levels.

4. Sampling parts from a batch can obtain a more accurate estimate of the total hidden quality loss. The number of failures within the batch can be simulated by transferring the total hidden quality loss to those parts causing it. This allows for the establishment of the hidden quality loss-reliability prediction models.

The stability and reliability of both models are verified through case analysis. Further comparison of two model shown that the model based on QEF is more accurate than the one based on AQF. This finding has significant implications for manufacturers seeking to improve part quality and reduce machining costs.

Acknowledgments

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