Research on machining allowance distribution optimization based on processing defect risk

Xiaonan Wu, Wei Dai*

School of Reliability and System Engineering, Beihang University, Beijing, China

* Corresponding author. Tel.: 86-138-1058-4286. E-mail address: dw@buaa.edu.cn

Abstract

It is necessary to control every key process to make sure the output quality of final product is stability. Because there existing many fluctuating factors during multistage manufacturing processes, it is inevitable lead to numerous manufacturing defects, which would make the quality of final product at risk. In this paper, a model about processing defect risk was proposed to measure the quality of products, which was associated with multistage machining allowance. Then, it was used to optimize machining allowance distribution program of multistage manufacturing process. A machining example of slide valve & sleeve matching parts was presented to verify the rationality of this model.

Keywords: Defect risk; Machining allowance; Process optimization; Multistage manufacturing process

1. Introduction

Bathtub curve of product life cycle is influenced by design, manufacturing processes and material aging. And manufacturing defect is the decisive factor in products’ early failure rate as well as inherent failure rate. One important measure to ensure the inherent failure rate of products is to optimize technology based on manufacturing defect formation mechanism and its compensation rules.

Manufacturing processes pay close attention to defects’ effect on products in order to guarantee the products’ inherent reliability to meet the design requirements as far as possible. Manufacturing defects can be divided into two main categories according to its specific manifestation mode: dominant defect and recessive defect. In general, dominant defect refers to the geometric defect, including geometry out-of-tolerance, geometric deformation, which can be detected directly in quality inspection section. Recessive defect mainly refers to the physical micro defect, including the precision shape deviation and position error, surface defect, mechanical stress defect and so on, which cannot be detected directly by quality inspection or the test cost is difficult to satisfy production efficiency. Recessive defect would gradually evolve into dominant defect under the environmental stress so that it is the root cause of product failure. Product’s wear resistance, corrosion resistance, fatigue strength and other mechanical physical characteristics are largely limited by recessive manufacturing defect and it will lead to product’s reliable life is difficult to meet the design requirements which not only affect the cost of equipment life cycle, but also affect the performance of equipment system, even related to the safety of people.

The concept of risk includes two aspects, one is the probability of unexpected event, and another one is the severity of its consequence. Manufacturing process risk refers to the product quality that cannot meet the specified requirements or the inevitable existence of quality loss. Processing defect risk can be measured through the distribution of defects and the severity of product quality loss. There are two ways for different processes’ incentive
functions to the defect distribution: positive and negative. The relationship between processes and defects are many-to-many mapping, as shown in Figure 1.

![Fig. 1. The relationship between processes and defects.](image)

The level of defect risk is associated with specific processing scheme. Different processes have different effects on defect distribution. It is necessary to optimize process to reduce processing defect risk. This paper defined the unit machining allowance’s contribution to manufacturing defect and the severity of defect influence according to the different processing technology experience. It is generally acknowledged that the larger machining allowance the greater contributions to defect. Then, the processing defect risk model is established to optimize machining allowance scheme of multistage manufacturing processes.

2. Processing defect risk model

The variation of processing parameters such as man, machinery, material, method, measure and environment, lead to defective products inevitably. Products with dominant defect could be detected as unqualified to be repaired or scrapped through quality inspection procedure. However, recessive defects cannot be detected directly and it would gradually evolve into dominant defect under the environmental stress, which lead to product quality problem.

Every procedure of machining process may be incentive to some kinds of defects, meanwhile, compensate for other kinds of defects which were accumulated by previous manufacturing procedures. The relationship between processes and defects are many-to-many mapping. Suppose that there are n key processes during machining a product, denoted by \( P_i, i = 1, 2, \ldots, n \) and it would bring about m kinds of defects, denoted by \( D_j, j = 1, 2, 3, \ldots, m \). \( d_{ij} \) denote the unit machining allowance contribution from the \( i \)-th process to the \( j \)-th defect. The contribution set between processes and defects can be described by \( D^p \), as follows:

\[
D^p = \begin{bmatrix}
    d_{11} & d_{12} & L & d_{1m} \\
    d_{21} & d_{22} & L & d_{2m} \\
    M & M & O & M \\
    d_{n1} & d_{n2} & L & d_{nm}
\end{bmatrix}
\]

The \( k \)-th machining allowance distribution program, denoted by \( X^k, X^k = [x_1^k, x_2^k, L, x_n^k], i = 1, 2, 3, \ldots, n \). \( x_i^k \) indicate the \( i \)-th process’ machining allowance. Actually, the total machining allowance of a product is certain as a result of the limitation of raw material and process design. That is to say \( \sum x_i^k = C \), \( C \) is a constant. It is generally recognized that the larger finishing allowance the better for defect compensation. However, due to the limitation of manufacturing cost and production schedule, the percentage finish machining allowance cannot very large. The influence of different defects on product quality is called severity, denoted by \( S \). The processing defect risk of the \( k \)-th machining allowance distribution program can be defined as \( R^k \):

\[
R^k = X_{ix} \cdot D_{ix} \cdot S_{ix}
\]

3. Application case

3.1. Case background

Precise couple with cylindrical matching surface is widely applied in servo mechanism to control pressure, oil-way and flow-rate. The most typical matching parts are Slide valve and Sleeve, as shown in Figure 2.

![Fig. 2. The sketch of slide valve-sleeve matching parts.](image)

The manufacturing process of slide valve-sleeve matching parts are critical because the dimensional accuracy and matching characteristic will affect performance of servo valve directly. Matching parts processing has become a bottleneck that restricting servo valve technology promotion. The main manufacturing defects include matching clearance out of tolerance, matching surface cylindricity deviation, the Burr of throttling work-side, roughness and residual stress.

Slide valve- sleeve is a couple of precision parts that should follow the principles of first roughing, then semi-finishing and last finishing. The technological process as shown in Figure 3. The tolerance clearance between slide valve and sleeve and their shape accuracy are decided by the allowance of matching finish process.

![Fig. 3. Technological process.](image)

There are two ways for matching finishing process: One is finishing slide valve outside surface to match with sleeve’s inner surface and another one is by finishing sleeve’s inside surface to match with slide valve outside surface. This paper studies the relationship between machining allowance distribution and machining defects. If the finishing allowance for sleeve inner surface is larger than the slide valve’s outside...
surface finishing allowance, it can be considered that is by finishing sleeve’s inner surface to match with slide valve outside surface and vice versa.

According to the technological design requirements, the bar diameter of slide valve is 12.8mm and the outer diameter $\Phi = 6.4$ mm. The cylinderity required for all surfaces is less than 1um and surface roughness is less than 0.1Ra. And the tolerance clearance between slide valve and sleeve should be controlled between 2um to 4um.

Hence, the machining allowance for sleeve’s inner surface is 6.4 (+0.002, +0.004) mm, and the machining allowance for slide valve’s outside surface is 6.4mm.

Machining allowance distribution principles can be established considering the actual processing characteristics and economic rationality:

- Rough machining allowance is larger than 10 times as much as the semi-finishing allowance, and at the same time, semi-finishing allowance is larger than 10 times as much as the finishing allowance;

- The unit rough machining allowance’s contribution to manufacturing defects is larger than semi-finishing, and at the same time, the unit semi-finishing allowance’s contribution to manufacturing defects is larger than finishing;

- The total machining allowance is certain;

- The tolerance clearance between slide valve’s outside surface and sleeve’s inner surface is 2-4um.

3.2. Application of processing defect risk model

There are six processes and five major defects in this application case according to the process documentation and experience, the manufacturing process information as shown in table 1. From the table 1, it can be get that $n=6, m=5$. The main manufacturing defects include matching clearance out of tolerance, matching surface cylinderity deviation, the burn of throttling work-side, roughness and residual stress.

First, the unit machining allowance’s contribution to manufacturing defects can be divided into ten levels that are represented by the number 1-10. The higher the level, the greater the degree of contribution. Minus sign indicates that is negative incentive to manufacturing defects. The unit machining allowance’s contribution set between processes and defects can be acquired based on the experience of engineers and inspectors, as showed in formula (3).

<table>
<thead>
<tr>
<th>Object</th>
<th>No.</th>
<th>P.</th>
<th>Allowance [um]</th>
<th>Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeve’s inner surface</td>
<td>1</td>
<td>Rough machining</td>
<td>x1</td>
<td>1. Burr</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Semi-finishing</td>
<td>x2</td>
<td>2. Cylindricity</td>
</tr>
</tbody>
</table>

$$\text{Table 1. Manufacturing process information.}$$

The objective function can be expressed as:

$$\text{max } R = -X_{x1} \cdot D_{x1} \cdot S_{x1}$$

$$\left\{ \begin{array}{l}
    x_1 - 10x_2 > 0 \\
    x_2 - 10x_1 > 0 \\
    x_3 - 10x_4 > 0 \\
    x_4 - 10x_3 > 0 \\
    x_5 + x_6 + x_7 > 6402 \\
    x_8 + x_9 + x_{10} < 6404 \\
    x_{11} + x_{12} + x_{13} = 6400
  \end{array} \right.$$  \hspace{1cm} (6)

The machining allowance distribution program was optimized by genetic algorithm and the results are shown in the following table.

$$\text{Table 2. Optimized machining allowance distribution program.}$$

$$\begin{array}{c|ccccccc}
  \text{Process} & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 \\
  \hline
  \text{Machining} & 5.7568 & 0.5777 & 0.0686 & 5.7660 & 0.5765 & 0.0575 & 0.0086
\end{array}$$
It indicates that the finishing allowance of sleeve inner surface is 0.0686mm, and the finishing allowance of slide valve outside surface is 0.0575mm. Therefore, proposed that, the better way for matching finishing process is by finishing sleeve inner surface to match with slide valve outside surface.

A servo valve factory had carried out the comparison tests to verify the rationality of the optimized program. Its original processing program was by finishing slide valve outside surface to match with sleeve inner surface, which is called hole-basic system of fits. The new processing program is by finishing sleeve inner surface to match with slide valve outside surface, which is called shaft-basic system of fits. And the test results are shown in Table.3

<table>
<thead>
<tr>
<th></th>
<th>Average tolerance clearance</th>
<th>Average residual voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original program</td>
<td>0.0025mm</td>
<td>4.38</td>
</tr>
<tr>
<td>New program</td>
<td>0.0021mm</td>
<td>3.36</td>
</tr>
</tbody>
</table>

The average tolerance clearance and the average residual voltage in new program is better than the original program. The result indicates that the optimized machining allowance program could be better at ensuring product quality and the rationality of processing defect risk model is verified.

4. Conclusion

Processing defect risk can be measured through the distribution of defects and the severity of product quality loss. In this paper, a model about processing defect risk is proposed to measure the quality of the products, which is associated with the processes of machining allowance. This paper defined the unit machining allowance’s contribution to manufacturing defects and the severity of defects’ influence according to the different processing technology experience. And use this model to optimize machining allowance distribution program. A machining example of slide valve & sleeve matching parts is presented to verify the rationality of this model.

However, it is deficient in quantitative calculation about the proposed processing risk model. The unit machining allowance’s contribution set was obtained just by experience. For future research, we intend to improved risk algorithm.

Acknowledgements

The authors acknowledge the financial support of Technical Foundation Program (grant JZSL2014601B004) from Ministry of Industry and Information Technology of P. R. China.

References