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Research Article

Dimension Measurement and Quality Control during the Finishing Process of Large-Size and High-Precision Components

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The accurate measurement and control of the geometric dimensions and shape errors of large-size and high-precision key components are key factor to ensure the machining quality of the equipment package. Aiming to address the urgent problems of poor measurement conditions, complicated error propagation, and difficulty in obtaining accurate measurement results, this research studied the measurement method and control of dimensional accuracy and geometric tolerance in the process of hole machining at room temperature, taking Metso MP 1250 cone level 6 precision point pair workpiece as the object. Through linear analysis and demonstration of quality problems in the existing processing technology, the influence of the expansion coefficient of the workpiece material, measurement error and other factors is analyzed. After correcting the temperature error model, many measurements were carried out in machining experiments, and the normal ability was analyzed by Minitab software. The experimental results showed that the workpiece temperature rises by 1°C, the workpiece will be deformed by 8.503 um. In the measurement process of high-precision and large-size components, the correction accuracy of the temperature error is affected by the combined influence of the model error, the material expansion coefficient error, and the temperature measurement error. The results of this study are of guiding significance for the measurement of the dimension and geometric tolerance precision of large-size and high-precision castings.

1. Introduction

The application of more high-tech has become an urgent and crucial task for the iterative upgrading of the machinery manufacturing industry. The focus of the manufacturing industry is shifting from hardware competition to software competition, from mechanization to intellectualization [1]. Comparing this development trend with the status quo of machining equipment and machining technology for large-size and high-precision components, it can be concluded that increasing the application of high-tech machining technology (especially in high-precision products) has become an inevitable demand for market development [2–5]. Large-scale mining machinery is a kind of power machinery whose cone is the key core component that burns fuel and directly converts heat energy into power. The accurate measurement and control of geometric dimension and shape error of large-size and high-precision key parts is the key factor to ensure the processing quality of the whole set of equipment. The main shaft of the mining machine has a large structural size, high design accuracy and presents a cone shape. It is the main bearing component in the cone-shaped shell of the mining machine. The operation process is similar to the inner and outer rings of the sliding bearing and belongs to liquid dynamic pressure lubrication. Therefore, this requires high surface roughness and shape accuracy of the main shaft and its matched shell. In recent years, with the increasingly fierce market competition, improving the finishing quality of the cone of large mining machines has become a top priority for further developing related machinery manufacturing enterprises.

At present, scholars from many manufacturing companies and research institutions at home and abroad have done a great deal of research on the key technology of mining machining cones [6, 7]. Based on experimental experiment system, Dogan et al. studied the physical requirements, structural characteristics, and technical requirements of the cone, analyzed the influence of stress-relief heat treatment process, welding process, and important cutting parameters (tool feed, cutting speed, etc.) on the quality of cone machining, and finally proposed a reasonable heat treatment method and machining process scheme for cone [8–11]. Mao et al. improved the structure of the flange cone. The flange was still formed by casting in his design, while the cone was manufactured by blanking and rivet welding. The two parts were welded at last, which not only saved raw materials and reduced the machining and manufacturing period, but also improved the overall quality of the flange cone [12]. Guo et al. applied virtual manufacturing technology to the machinery manufacturing process. They established the production process and production system model and virtual model, realizing the connection between the virtual manufacturing environment and the real manufacturing environment [13, 14]. It can be seen that both improving measuring tools and applying virtual manufacturing technology play an indispensable role in the machining of high-precision cones. Virtual simulation technology, comprehensively using the display and control technology of computer graphics system, can effectively improve the machining efficiency and quality. Given the related machining parameters of the machining object, the simulation optimized machining process can guide the actual machining process [15, 16].

From the perspective of MP1250 cone machining and manufacturing quality, the application of virtual manufacturing technology can effectively improve the quality of machining and optimize machining procedure, tool path, cutting parameters, blanking allowance and process structure, and reduce interference between fixtures and workpieces, and collision of machine tools, etc. [17, 18]. Applying the modular design method to the production process of remanufactured products can effectively reduce machining costs and improve the efficiency and accuracy of assembly [19]. Because different manufacturing companies have different processing places, changes of factory ambient temperature can affect the processing quality of high precision products [20], so the modular design is rarely applied in the research on machining cones of large mining machines. There are generally two measures to address this. One is to strictly control the temperature of the measured workpiece in a standard state [21]; the other is to correct the temperature error [22]. The first method requires high-precision measurement conditions, which is generally difficult to achieve, whereas the second is simple and easy to implement, and it is economical and applicable [23–25]. This suggests that the machining error control with temperature factors considered needs further research in high-efficiency machining technology, which is the significance of the present research.

In view of this, this research intended to take the Grade 6 precision spot facing work of Metso MP1250 cone as the object to study the measurement method and control of the dimensional accuracy and geometric tolerance of the high-precision spot facing work during machining. Based on the linear analysis and demonstration of quality problems existing in the existing machining process, this paper summarizes and analyzes the main factors affecting the machining quality of high-precision hole. Under the existing machining workshop environment and temperature conditions of the target enterprise, the influence of the expansion coefficient of the workpiece material, measurement error and other factors is analyzed. Before being used to guide on-site machining, the temperature error model was revised, and batches machining experiments were carried out to verify and determine reasonable machining methods and parameters, and to solve the problems of low machining efficiency and unstable quality. The research can provide a practical basis for the finishing process scheme of key parts with large size and high precision.

2. Analysis of Cone and Dimension Precision of GP Series Crusher

Metso GP series heavy cone crusher mainly comprises a frame, fixed cone, moving cone, spring mechanism, bowl-shaped shaft bracket, transmission parts, and auxiliary systems, as shown in Figure 1. When in operation, the motor drives the eccentric sleeve to rotate through the V-belt, large pulley, transmission shaft, a small bevel gear and bevel gear. The cone crusher axis rotates and swings under the force of the eccentric sleeve, so that the surface of the crushing wall approaches and leaves the surface of the rolling mortar wall. As a result, the material is continuously impacted, squeezed, and bent in the annular crushing cavity composed of the fixed cone and the movable cone until it is broken. The cone is one of the key components under great stress. It becomes the nodus during the machining due to its high precision and large size. Specifically, there are many holes, shafts, and keyway dimensions on the cone having transition fit and interference fit with small tolerance range, which are affected by the environmental factors of the machining plant, making it difficult to obtain accurate measurement values during the machining process, thus failing to meet technical requirements of assembly. Part of the design size of the cone is shown in Figure 2. In the process of machining, it is necessary to measure the process size of high-precision hole repeatedly. The basic dimension of the three holes are about $\varphi 1000$ mm, with the dimensional tolerance reaching IT5-IT6 precision, and the tolerances of radial runout and hole axis perpendicularity are both within 0.05 mm, as shown in Table 1.

3. Existing Machining Quality Problems

The research object of this paper is one of the businesses we have only carried out in recent years. Since the working hours of continuous processing of a cone reach 36 days. Through the statistical classification of 17 products with quality defects on-site, the main reasons for the quality problems of the products were summarized as shown in the following figure.

Figure 1: Structure diagram of cone crusher.

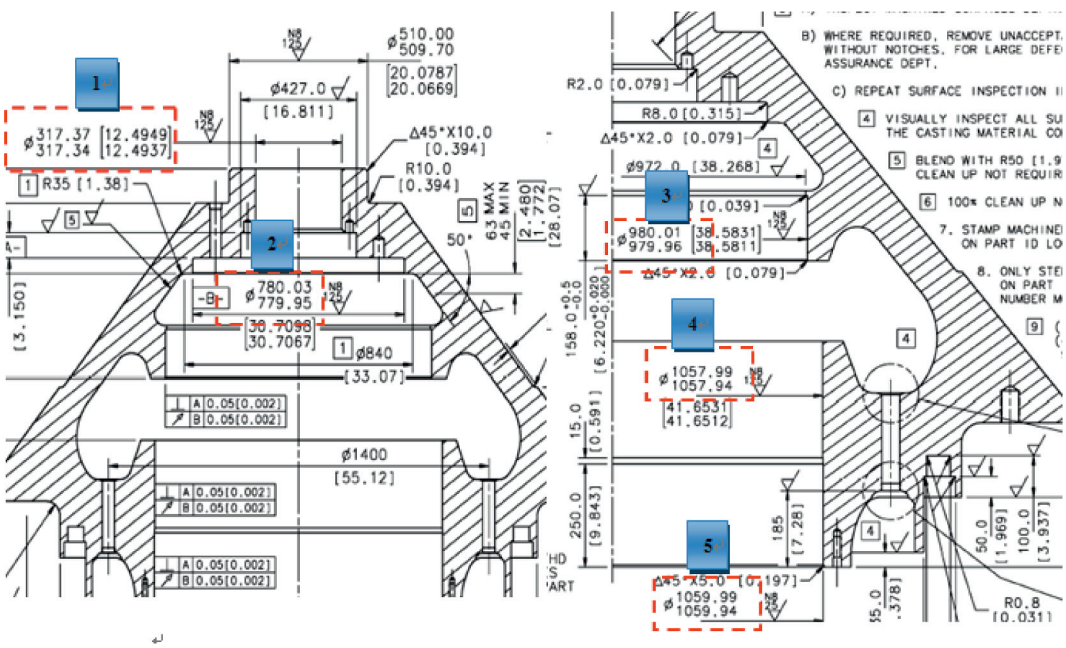

Figure 2: Dimensions of the cone structure.

Table 1: Dimension precision of high-precision holes.

SN	1	2	3	4	5
Drawing dimension (mm)	ϕ 317.34	ϕ 779.95	ϕ 979.96	ϕ 1057.94	ϕ 1059.94
Tolerance range (mm)	0.03	0.08	0.05	0.05	0.05
Precision level	IT5	IT7	IT6	IT6	IT6

Linear analysis and field demonstration showed that indirect measurement was often adopted during the machining process due to the large diameter of the fine turning hole. The improper use of the measuring tool was one of the reasons for the measurement error. In contrast, the large size of the workpiece, high heat capacity, the unstable temperature at the site, temperature changes in the workpiece during machining, and the complex composite error propagation of the measuring tool under the influence of the temperature were the leading causes of the unstable measurement accuracy. It can be seen from Figure 3 that among the various defects that cause the unqualified cone machining, the excessive machining of the high-precision spot facing work was the main reason. Among the ten defective products with excessive spot facing work, nine products are due to the excessive machining along the diameter direction of the hole, and the rest is due to the excessive machining along the axial dimension, which is concentrated in the SN 3, 4, and 5 holes in Table 1. However, further analysis of the processing data on the processing record shows that the measured data before and after each processing are within the required size range.

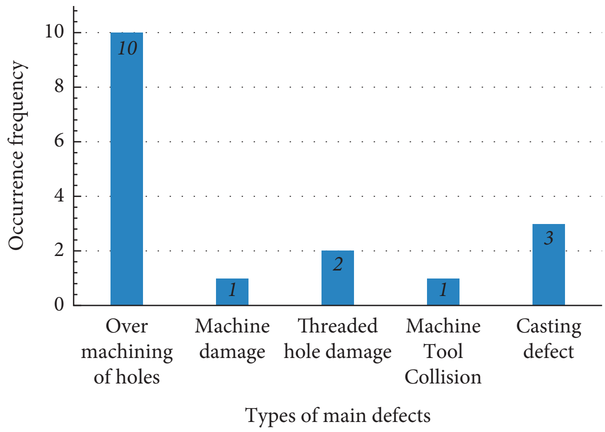

FIGURE 3: Analysis of quality problems during cone machining process.

4. Correction of the Temperature Error Model

Because the temperature affects the measurement results, the current correction method was to adjust the expansion coefficient of the material of the component, the relationship between the actual temperature, the standard temperature deviation, and the length of the component. That is, at the same temperature difference, the larger the nominal dimension of the measured workpiece, the more the temperature error increases, and the more sensitive it is to changes in temperature. The relationship between temperature and length can be expressed by the following functional equation:

$$\Delta L = L\alpha(t - 20). \tag{1}$$

Where, ΔL is the dimensional change, L is the nominal dimension of the measured workpiece, α is the coefficient of linear expansion of the object (1/°C), t is the temperature of the object (°C).

From equation (1), it can be seen that the dimensional change of the measured workpiece is proportional to the temperature difference with the standard temperature of 20°C and the nominal dimension of the workpiece. Therefore, ΔL is also called the temperature error correction value.

This modified model can meet the requirements when applied to small-size or low-precision measurement occasions, and the error after the correction can be ignored. However, for the high-precision measurement of large-size workpieces, the residual error after the correction still significantly impacted the precision. Therefore, based on the precision analysis, corresponding precision assurance measures were proposed to ensure high-precision measurements for large-size workpieces. The main factors affecting the accuracy of temperature error include the error of the temperature error correction model, the linear expansion coefficient of the material, temperature measurement error and so on. In addition, considering the large fluctuation of ambient temperature in the processing plant, the influence of temperature gradient on the measurement accuracy is also included.

Under a uniform temperature field of the measured workpiece, the temperature error correction value can be obtained through the following equation:

$$\Delta L = L\left(\alpha\Delta t + \beta\Delta t^2\right), \tag{2}$$

where α is expansion coefficient of the material, β is the secondary expansion coefficient of the material, and for commonly used materials, $\beta \le 10^{-7}$/°C. Compared with equation (1), it can be seen that the traditional error correction formula is an approximate formula obtained by ignoring the above quadratic items. Because the thermal expansion coefficient of the higher-order term was very small, and expansion coefficients might be positive or negative, it can offset some deformation error. The formula was simplified as shown in equation (2). Thus, the error caused by the linearization of the temperature error correction model can be obtained as

$$\delta_m = L\ \beta\Delta t^2. \tag{3}$$

Then, the maximum uncertainty component μ_1 caused by the error of temperature error correction model can be expressed as

$$\mu_1 = L\left|\beta\Delta t^2\right|. \tag{4}$$

As can be seen from the above equation, the measurement uncertainty caused by the error of the temperature error correction model increased with the increase of the nominal dimension of the measured workpiece and the rise of the temperature. On the other hand, the measurement of temperature error also had a great influence on the measurement accuracy of large-sized workpiece. Assuming that the temperature measurement uncertainty is $\mu_{\Delta t}$, then the measurement uncertainty μ_2 caused by the temperature measurement error can be expressed as

$$\mu_2 = \left|\frac{\partial \Delta L}{\partial \Delta t}\right| \mu_{\Delta t} = L\ \partial\Delta t. \tag{5}$$

The same conclusion can be obtained: μ_2 increases with the increase of the measured dimension, the coefficient of linear expansion, and the uncertainty of the measured temperature.

The current expansion coefficients of various materials provided in the engineering manual were the evaluation values of the material expansion coefficients obtained from the thermal deformation test within a large range of temperature on round bar specimens with a certain diameter-length ratio. Compared with the research object, the evaluation value is uncertain. Assuming the measurement uncertainty caused by the error of the material expansion coefficient is u_3, it can be expressed as

$$\mu_3 = \left|\frac{\partial \Delta L}{\partial \alpha}\right| \mu_0 = L|\Delta t|\mu_0. \tag{6}$$

Where, μ_0 is the uncertainty of the material, usually being 2×10^{-6}/°C.

When measuring the large-size workpieces studied in this paper, the differential expansion coefficient of the measured component material should be determined first, and then use this coefficient to correct the temperature error. Using this diagram, the error of the temperature error correction model can be compensated in the accurate determination of the expansion coefficient, which significantly reduced the uncertainty of measurement caused by temperature changes. In summary, the temperature error correction model in the measurement of a large-size workpiece can be expressed as

$$\Delta L = L\left(a_{t2}t_2 + a_{t1}t_1\right). \tag{7}$$

Because the cone material of this research object was mainly alloy steel, the φ1057.94 mm fine turning hole in Figure 2 was taken as an example. According to the actual temperature of the machining site, the following values were taken after calculating as per the applicable temperature range and checking the engineering manual:

$$\begin{aligned} t_2 &= 19.85^{\circ}\mathrm{C}, \\ a_{t2} &= 8.0342 \times 10^{-5}\,\mu\mathrm{m}, \\ t_1 &= 9.84^{\circ}\mathrm{C}, \\ a_{t2} &= 8.0334 \times 10^{2}\,\mu\mathrm{m}. \end{aligned} \tag{8}$$

Then, at the first temperature gradient,

$$\begin{aligned} \Delta L_1 &= L\left(a_{t2}t_2 + a_{t1}t_1\right) = 85.090\ \mu\mathrm{m}, \\ \frac{\Delta L_1}{\Delta t} &= L\left(a_{t2}t_2 + a_{t1}t_1\right) = \frac{8.500\,\mu\mathrm{m}}{^{\circ}\mathrm{C}}. \end{aligned} \tag{9}$$

Similarly, at the second temperature gradient, the following values were taken:

$$\begin{aligned} t_2 &= 29.90^{\circ}\mathrm{C}, \\ a_{t2} &= 8.0351 \times 10^{-5}\,\mu\mathrm{m}, \\ t_1 &= 19.85^{\circ}\mathrm{C}, \\ a_{t2} &= 8.0342 \times 10^{2}\,\mu\mathrm{m}. \end{aligned} \tag{10}$$

It was obtained that

$$\begin{aligned} \Delta L_2 &= L\left(a_{t2}t_2 + a_{t1}t_1\right) = 85.454\,\mu\mathrm{m}, \\ \frac{\Delta L_2}{\Delta t} &= L\left(a_{t2}t_2 + a_{t1}t_1\right) = \frac{8.503\,\mu\mathrm{m}}{^{\circ}\mathrm{C}}. \end{aligned} \tag{11}$$

After comparing with the above calculation results, it was found in the in-process measurement of the research object, every 1°C increase in casting temperature would cause 8.503 μm dimensional deformations of the casting. Therefore, in the actual machining of the cone casting, the casting temperature must be measured to compensate for the effect of temperature on the dimensional measurement.

5. Improvement and Implementation of Measurement Scheme

In order to avoid the influence of the operator's body temperature on the measuring tool and the errors caused by the expansion of the measuring tool due to the hand temperature, gloves with good heat insulation ability should be worn when measuring, with the hand holding the tool no more than 2 min. Therefore, a special measuring tool was designed for cone alignment and quick measurement, as shown in Figure 4.

This tooling includes a handle, a laser generator (the red line refers to the laser beam), the body, the high progress reference guide rail on the back of the body, and an adjusting screw. The adjusting screw can adjust the upper and lower positions of the laser. The supporting surface is in contact with the processing surface of the workpiece, and the supporting surface can be changed into a circular one (measuring coaxially). The horizontal and numerical distance between the laser beam and the adjacent surface is determined. If the height deviation between two distant surfaces is measured, the tooling will contact one side and the laser beam will hit the other side. Therefore, measuring the distance between the laser beam and the surface will measure the distance between the two surfaces.

The specific implementation steps were as follows:

(a) After machining is completed, place the workpiece to be tested for more than 30 minutes, so that its temperature is the same as the ambient temperature. As shown in Table 2, the variation of the factory ambient temperature with time on a certain day during the measurement process was obtained.

(b) After measuring the current temperature of the measured workpiece and combining the above compensation conclusion, the gradual deformation compensation at the current temperature was calculated.

(c) The current dimension of the workpiece to be measured was measured through the repetitive measurement method, i.e., each point was measured in no less than three groups, each group no less than three times, and the average value was taken as the final result of the measurement point.

(d) The final dimension of the object to be measured was determined. According to the principle of obtaining the sum of the inner diameter difference and the outer diameter of the hole, after calculating the size value and deformation compensation value of the workpiece at the current temperature, the final size of the object to be measured was determined. The compensation relationship was obtained as shown in Table 3. The machining results of a ₵ 1057.94 mm spot facing work were measured. The errors were obtained through a comparison between different measurement results of different batches and the drawing results, as shown in Figure 5.

Measurements were performed according to the above requirements, and the measurement data were organized and recorded after completion, according to the Bessel formula:

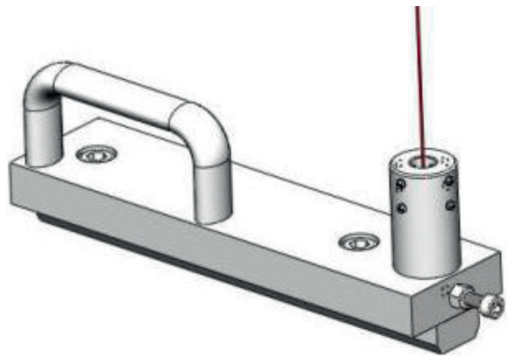

Figure 4: Laser alignment measurement tool.

Table 2: Time-varying temperature in plant environment (September).

Temperature (°C)	21.5	19	20	24	25	26	24	23
Time (h)	00 : 00	03 : 00	06 : 00	09 : 00	12 : 00	15 : 00	18 : 00	21 : 00

Table 3: Measured dimension compensation.

In situ temperature (°C)	19	20	21	22	23	24	25	26
Inner diameter compensation (μm)	+8.503	0	−8.503	−17.006	−25.509	−34.012	−42.515	−51.018
Outer diameter compensation (μm)	−8.503	0	+8.503	+17.006	+25.509	+34.012	+42.515	+51.018

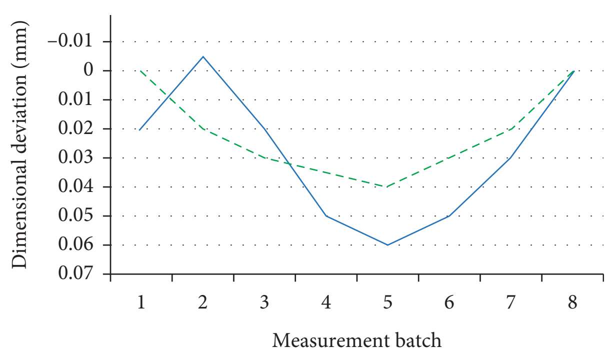

Figure 5: Dimensional deviation among different measurements.

$$S = \sqrt{\frac{\sum_1^i (x - x_i)^2}{i - 1}}. \tag{12}$$

Calculate the standard deviation of the experiment, and according to the principle of maximum error, eliminate the result that the reading deviates from the average value by more than 3 times. The Minitab software was used to carry out statistical analysis of normal capacity and process capability analysis. Taking the ₵ 1057.94 mm hole as an example, its normal capacity distribution was obtained, as shown in Figure 6.

The method of normal capability analysis is used to evaluate the potential (intragroup) capability and overall capability of the process according to the normal distribution. In this analysis, the following operations are mainly performed: determine whether the process can generate output that meets the processing requirements. Compare the overall capability of the process with its potential (in group) capability to assess opportunities for improvement. When performing the analysis, specify the lower or upper specification limit, the limit size of the current machined hole, to define the process requirements. This analysis will be relative to the expansion of the specification limit evaluation process data. When the process is capable, the process expansion is less than the specification expansion. This analysis can also indicate whether your process is centered and reaches the target value. In addition, this analysis will estimate the ratio of products that do not meet the specifications.

Multiple sets of measurement results of holes with a machining target of ₵ 1057.94 mm showed that the measurement process was in a steady-state, and 99.73% of the characteristic values of the processed objects were scattered in the interval $[\mu - 3\sigma, \mu + 3\sigma]$. In other words, almost all product characteristic values fall within the range of 6σ, indicating that the measurement evaluation process capacity was consistent with the specified requirements.

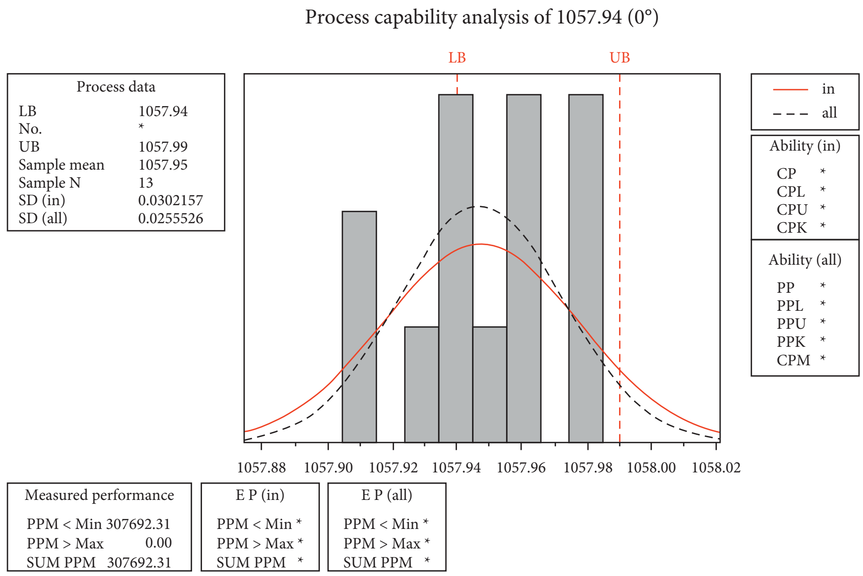

Figure 6: Normal capability distribution.

6. Conclusion

In the measurement process of large-size, high-precision components, the correction accuracy of the temperature error is affected by the combined influence of the model error, the material expansion coefficient error, and the temperature measurement error.

A comparison of the results of several measurements and calculations showed that every 1°C increase in casting temperature would cause a deformation of 8.503 um to the casting dimension. In the actual casting process, the casting temperature must be measured to compensate for the effect of temperature on the dimension measurements.

According to the corrected error model and measurement compensation values, the measurement process capability of the measured object completed by the improved measurement scheme showed that the measurement process was in a stable state and the measurement process capability is sufficient to meet the machining quality. The results of this study provide guidance for carrying out precision measurement of the dimension and geometric tolerance of large-size, high-precision castings.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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