Calculation Formula of Positioning Error Based on Three Dimensions and Four Datum

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Abstract. Calculation of positioning error is difficult for engineers because of its invisibility in forming process, as well as coexistence of various forms. This paper is focused on the calculation of fixture location error from the novel direction to deepen understanding of error origination. In contrast to previous investigations, the authors have developed an equation to compute fixture location error based on three dimensions and four datum. This equation which is given after differential operation allows resource of location error. The findings from the differential equation shows that the fixture location error consists of the change in three misalignments of process datum and locating datum, spatula datum and locating datum, locating datum and stop datum respectively under general condition, and the value of fixture location error is gotten after simple operation of their three components listed above. And in case of locating element of plane or (and) Vee block especially, the fixture location error depends on the change in the distance of process datum and spatula datum. The work brings help to analysis positioning error and its conclusion indicates the method to reduce the value of positioning error quickly.

1. Submitting the manuscript

The fixtures in machining are used to provide accurate and repeatable unique positing of the part and sufficient work-holding to eliminate movement of the part under machining or assembly loads. The costs related to fixture can account for nearly one fifth of the total cost of a manufacturing system [1]. On the other hand, approximately forty percent rejected parts due to dimensioning errors are attributed to poor design of fixtures [2].

Many researchers have investigated the influence of fixture-workpiece system on the aggregate accuracy of machining. The objective of researchers is to improve workpiece location accuracy through optimization during the process of fixture planning, design and manufacture. The researches have been mostly focused on: contact analysis, finite-element analysis (FEA), force analysis, kinematic analysis.

Meyer and Liu brought out a methodology for fixture layout under dynamic machining forces and determination of optimal positions of locating elements and clamping forces [3]. Li and Melkote found an optimal synthesis approach for fixture layout and clamping force considering workpiece dynamics during machining and optimized clamping force for a multiple clamp fixture subjected to a quasi-static force [4, 5]. Amaral et al. developed an algorithm to automatically optimize clamp locations, clamping forces and fixture support in employment of 3-2-1 locating method, to increase machining accuracy by minimizing workpiece deformation [6]. Nee et al. invented a sensor-assisted fixture capable of delivering varying clamping loads, calculated from a quasi-static model, to find minimum of
workpiece distortion [7]. Sielenaler and Melkote gave a fixture-workpiece model using FEA to investigate the influence of various parameters on workpiece deformation, including the compliance of the fixture body, contact friction and mesh density [8]. Raghu and Melkote built force-based clamping sequence model to analyze the effects of fixture clamping sequence on workpiece location errors, and they designed an algorithmic procedure to understand how forces and deformations change as the clamp applied sequentially is presented [9]. Tian et al. gave an approach to optically select the locating positions of workpieces and identify feasible clamping regions in terms of the requirements of form-closure principle for fixture layout [10]. Sanchez et al. calculated the contact load and its distribution and valid clamping regions in machining process [11]. Ratchev et al. proposed the behaviour prediction methodology for complex fixture-workpiece during machining processes [12]. Hazarika et al. presented a setup planning methodology for prismatic workpieces by formulating the objective function to minimize the maximum of locating elements reaction forces [13]. Chaari et al. modelled kinematical deviation due to workpiece locating and relocating, and determined dynamic displacements caused by clamping and machining force [14]. Vishnupriyan computed the effect of different layouts and various clamping forces on machining error in terms of system compliance and workpiece dynamics [15]. Selvkumar et al. presented a hybrid scheme to design an optimum fixture layout to reduce the maximum elastic deformation of workpiece from forces while machining [16].

Several important conclusions stem from the analysis of previously discussed investigations. Namely, elastic or plastic workpiece deformations in clamping process can greatly influence final workpiece accuracy. On the other hand, detachment of workpiece from locating elements during machining can lead to less efficient clamping process. Minimization of fixture-workpiece compliance should be paid special attention to fixture layout optimization when considering modern cutting regimes or machining thin-walled and complex-geometry workpieces.

Investigations published so far, basically deal with dynamic behaviour analysis of contact interfaces between fixture elements and workpiece. It is impossible to thoroughly understand the fixture-workpiece interface behaviour because of complex-geometry and various clamping/locating requirements of workpiece machined. The authors maintain that comprehensive analysis of dynamic behaviour and optimization of fixture elements requires, first of all, a dedicated instrument capable of testing of physical models which represent the fixture-workpiece interface behaviour; last but not least, understanding of location error resource and formation of location error. With this in mind, investigations in others of this paper are followed: Four datum and two dimensions formed in locating process are reviewed in section 2, and the computational formulas of process dimensions and dimension error are deduced in section 3, then an example to validate the formula presented is taken in section 4.

2. Review of four datum and two dimensions formed in locating procession

During the use of fixture, the following requirements should be met with, namely, the interface contact between fixture element and certain surface of workpiece should be kept, and the clamping force should be controlled firmly so that the maximum of locating elements reaction forces can be accepted. Once the contact between fixture locating element and surface of workpiece comes into being, the interface on fixture element and workpiece can be determined through stop datum and locating datum respectively. The other two are called as process datum on workpiece and spatula datum on fixture. Based on the above description, the process distance is defined between face to be machined and process datum, while the spatula distance between working face of tool setting element and spatula datum is done. Figure 1 is used as schematic drawing of fixture-workpiece, in which the locating element is central spindle, and workpiece with curve outer surface has central hole in the direction of itself axis, and their two parts are engaged in locating process. Where A- process datum; B- spatula datum; C- locating datum; D- stop datum; M- machining surface; N - interface contact; 1- workpiece; 2- locating element; 3 -fixture; 4- tool; 5- plug gauge; 6- tool setting element.
3. Computational formulas of process dimension error

The map of dimension geometrical relationship is drawn in Fig.2 to investigate the influence factors of process dimensions error. The outer line on cylindrical workpiece, namely process datum stands for A, and the theoretical center of workpiece is C’, then the distance of A and C’ is the diameter of workpiece R. On the other hand, the inner circle on the workpiece is the limit surface, which constitutes interface contact with outer surface of locating element. And the theoretical center of inner circle on the workpiece is represented as C. So the distance between C and C’ is named as concentricity error. Correspondingly the theoretical center of locating element, that is to say, stop datum is named as D, and then DC stands for the distance between stop datum and locating datum. The spatula datum B usually lays on the worktable of machine, CB is used to express the distance of locating datum and spatula datum, DB is expressed as the distance between stop datum and spatula datum, which is kept constant in one machining operation for one group of workpieces. Finally the distance of stop datum and process datum is stood as CA, E is the working surface of tool aligner, and the distance of E and B is named as tool setting dimension, and the distance between E and M equals to size of the plug gauge, MA stands for process dimension. The following examples in next part will be used to specify carefully.

From the Fig.2, the following equations are gotten in the terms of geometric diagram.

\[ MA + s + EB = R - CC' + CB \]  \hspace{3cm} (1)
\[ CA + CC' = R \]  \hspace{3cm} (2)
\[ DB = DC + CB \]  \hspace{3cm} (3)

where MA is written as A₁, and EB is done as A₂ whose size is regarded as constant in machining group of workpieces, and CC' is written as e.

Equations 1, 2, 3 are rewritten as followed:
\[ A_1 = (R - CC') + CB - (e - A_2) \]  
(4)
\[ CA = R - e \]  
(5)
\[ DC + CB - DB = 0 \]  
(6)

By substituting Equation 5 into Equation 4,

\[ A_1 = CA + CB - (e - A_2) \]  
(7)

By adding Equation 6 into Equation 7

\[ A_1 = CA + CB - (e - A_2) + 0 \]
\[ = CA + CB - (e - A_2) + DC + CB - DB \]
\[ = CA + 2CB - (e + A_2 + DB) \]
\[ = f(A, B, C, D) - k \]
\[ k = e + A_2 + DB \]  
(8)

The following findings are derived from the equation 8.

Process dimension is divided into two subparts, namely, \( f \) and \( k \). Among them, \( f \) is three dimensions which are \( CA, CB, \) and \( DC \), they come from the four datum which are the \( A, B, C, \) and \( D \), and they take direct influence on size of process dimension. Among them, the effect of \( CB \) on dimension is bigger than other two factors, which is derived from the coefficient before them.

And \( k \) is three dimensions consists of the tool setting dimension, distance between stop datum and spatula datum, tool setting dimension and workpiece’s geometrical characteristics such as concentricity error.

After the differential operation on equation 8, the following equation 9 is gotten:

\[ d(A_1) = d\{ f(A, B, C, D) - k \} \]
\[ = d(CA) + 2d(CB) + d(DC) \]  
(9)

where \( d \) stands for differential operation.

During of machining one group of workpiece, the position of \( B \) and \( D \) is fixed while that of \( C \) an \( A \) takes change. And the value of differential operation on \( k \) is zero whose components are regarded as constant value in this kind of machining. So the process dimension error stems from change in the three misalignments of \( A \) and \( C \), \( B \) and \( C \), \( C \) and \( D \) respectively. And the value of fixture location error can be gotten after simply operation on their three listed above.

Based on the analysis above, the value of location error is naturally the simple operation of change in three misalignments of process datum and locating datum, spatula datum and locating datum, locating datum and stop datum respectively.

Once the misalignments of \( C \) and \( D \) does not occur, the process dimension error stems from two misalignments of \( A \) and \( C \), \( B \) and \( C \) respectively. In this case, the process dimension error depends on the change in the misalignment of \( BA \), and which can be seen in locating procession. The following examples in next part will be used to specify carefully.

4. Example of computer of fixture location error

Described as figure 3, the location of workpiece is done by the combination of plane and half of V-block. The process dimension is \( h_1 \) and \( h_2 \), whose process datum is respectively \( A_1 \) and \( A_2 \). And \( B \) is spatula datum; the corresponding dimension of two datum is \( A_1B \) and \( A_2B \). Their two dimensions are projected into the direction of \( h_1 \) and \( h_2 \), namely, \( A_1C \) and \( A_2C \).
Based on geometry in figure 3, the following equation 10 is gotten:

\[ \Delta h_i = \Delta A_i C = \Delta (A_i D + DC) \]
\[ = \left( \frac{1}{\sin \alpha} \right) \delta d / 2 + 2 \left( \frac{1}{\tan \alpha} \right) \delta L \]

(10)

\[ \Delta h_2 = \Delta A_2 C = \Delta (A_2 D - A_1 A_2 + DC) \]
\[ = \left( \frac{1}{\sin \alpha} \right) \delta d / 2 - \delta d / 2 + 2 \left( \frac{1}{\tan \alpha} \right) \delta L \]

where, \( \Delta h_i (i=1,2) \) is expressed as location error when machining process dimension corresponding. \( A_i C \ (i=1,2) \) stands for the component of distance of two datum of \( A_i \ (i=1,2) \) and \( B \) in the direction of \( h_i \ (i=1,2) \).

5. Conclusions

After the analysis above, the findings are derived from.

1. The reason for location error is the misalignments of process datum and locating datum, spatula datum and locating datum, locating datum and stop datum respectively.

2. When the misalignment of locating datum and stop datum does not occur, the size of location error depends on the change in the distance of process datum and spatula.

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