Methods for Improving the Accuracy and Repeatability in the Position of a Workpiece in Chucking

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Abstract

Significant improvements have been made in the performance of CNC machine tools due to the active research over the last several decades. However, the research and understanding on chucking accuracy have not been adequate. Nor has any systematic methods been reported for on chucking accuracy, especially in terms of the repeatability and the accuracy in the position of a chucked workpiece. The needs for the improvements in chucking accuracy has been existed since chucking has been the bottleneck in the form accuracy of a workpiece as the accuracy of machine tools improved significantly over the last several decades. However, the need was not very strong since turning has not been considered as the finishing process for the production of precision mechanical components such as bearings and shafts. After recent studies have demonstrated the benefits of hard turning in terms of surface integrity over other abrasive machining processes as a finishing process, a strong need emerged to improve chucking accuracy to enable the implementation of finish hard turning for the production of precision mechanical components. In this study, systematic methods for improving the accuracy and repeatability in the position of a chucked workpiece have been sought. Factors affecting the positioning accuracy and repeatability of a chucked workpiece have been identified. In addition, the characteristics of these factors, as well as their effect on chucking accuracy, were given. From the results, a chucking error map that summarizes the relations between these factors and the positioning error of a chucked workpiece was created. A series of error reduction experiments were carried out based on the results of the earlier works. The experimental results showed the possibility that the knowledge created in this study could be used effectively to improve the positioning accuracy and repeatability of parts in chucking and other work/tool holding operations.

Keywords: Chucking accuracy; Concentricity; Error budgeting; Error reduction; Finish hard turning

1. Introduction

There have been significant advances in the performance of CNC machine tools and the quality of cutting tools due to the active research over the last several decades. However, the research and understanding of chucking in term of the positioning accuracy and repeatability of a chucked workpiece has not been adequate. Nor has any systematic method been reported for improving chucking accuracy, especially in terms of the repeatability and the accuracy in the position of a chucked workpiece. The needs for the improvements in chucking accuracy has been existed since chucking has been the bottleneck in the form accuracy of a workpiece as the accuracy of machine tools improved significantly over the last several decades. However, the need was not very strong since turning has not been considered as the finishing process for the production of precision mechanical components such as bearings and shafts [1,2].

Hard turning is a term to describe the machining of hard materials, especially hardened steel. Traditionally, hard turning has not been considered as a finishing process for the production of these components due to the poor surface integrity and form accuracies. After recent studies have demonstrated the benefits of hard turning in terms of surface integrity, production efficiency and costs over other abrasive processes as a finishing process, a strong need has existed to improve chucking accuracy to enable the implementation of finish hard turning for the production of precision mechanical components [1,2,3].

In this work, systematic methods for improving the accuracy and repeatability in the position of a chucked workpiece have been sought. The goal of this paper is to develop an error map that shows the relations among the factors on affecting chucking error and the effects of these factors on chucking error. Another objective of this study is to develop methods for minimizing the chucking error of a cylindrical workpiece in order to help implement hard turning as a finishing process for the production of precision mechanical components.

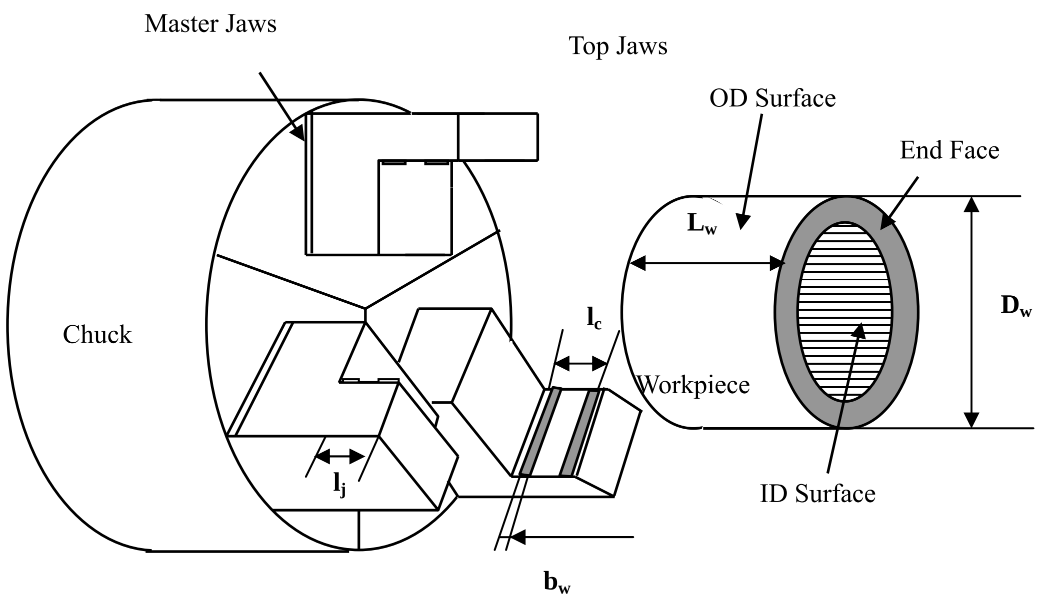
2. Error Budgeting

2.1 Basics of chucking error and research scope

Chucks are the devices that are most frequently used for the clamping of cylindrical workpieces. Their job is to center the workpiece to the spindle of a machine tool to the required degree of accuracy and to support it securely against the cutting force and to rotate it. If clamping is not sufficiently accurate, deviations in shape and position of the workpieces will occur and the dimensional and form accuracy of the machined workpiece will be degraded. This research covers the error budgeting and reduction of chucking error in a range of chucking/clamping situation where a cylindrical workpiece is overhung clamped. The workpiece is to be machined in turning that requires more than 1 set-up to finish. A cylindrical workpiece in this study includes a solid cylinder, a ring-shaped workpiece and a disk-shaped workpiece.

- *Nomenclature*

The majority of the following notations in Fig. 1 are based on the ANSI B5.8-1972, the American National Standard of Chucks and Chuck Jaws. Some of the notations that are not available directly from the Standard were adopted from other literatures on chucking [4,5,6,7].



$\mathbf{D_w}$**:** Workpiece Diameter $\mathbf{l_c}$**:** Clamping Length (Effective) $\mathbf{L_w}$**:** Workpiece Length $\mathbf{b_w}$**:** Width of Contact Band

Fig. 1. The definitions of parameters in chucking used in this work.

2.2 Definitions of chucking error

According to Pahlitzsch *et al*.[5], the deviations in shape and position which occur in the workpiece can be taken as a basis for defining chucking error. When a cylindrical workpiece is being machined, deviations from the ideal cylindrical shape may occur. When measured vertically to the axis, the deviation is called roundness error. When measured in the longitudinal section of the axis, the deviation is called straightness error (error of roundness and parallelism). Also, deviations in the position of unmachined surfaces can occur in the workpiece against the surfaces which develop during machining. The last deviation is called the deviation in the position of the workpiece.

Those deviations are measured in the form of radial run-out and axial run-out by means of experiments with clamped rotating test bars using probes. Even if the term, chucking error, may represent all sorts of errors caused by chucking operation in a broad sense, the chucking error of a workpiece conventionally represents the deviation in the position of the workpiece due to inaccurate chucking [5]. According to Ema *et al.* [4], the chucking error was defined as the eccentricity of a test bar. In this paper, the positioning error of a workpiece in chucking is defined as the deviation of the center of unmachined surface from the center of the machined surface in the plane of measurement.

2.2 Identification of factors affecting the accuracy and repeatability of the position of a chucked workpiece

• *Factors identified from literature review*

A machine tool, a chucking device and cutting tools have been considered as separate entities, but their performance relies on the ability to function in harmony [7]. The work holding requires particular attention since its performance is critical. An improper chucking system can restrict the performance and accuracy of the machine tool and limit a machine's use. There have been a number of studies on chucking accuracy [4,5,6,7]. Table 1 summarizes the factors identified by these studies and their characteristics.

Table 1 Summary of factors affecting chucking error which were identified from the literature

Name of factor	Error type	Description of error
Radial displacement error of Individual jaws	Geometric	Internal wear of chuck components and backlash, geometric deviation of chuck components/clamp
Geometric error of workpiece	Geometric	Caused by the previous process ex) Diameter deviation, roundness error, squareness error
Taper in jaw alignment	Geometric /dynamic	Artificial taper : beneficial to chucking rigidity, Detrimental to chucking accuracy
Curvature difference between workpiece and jaw	Geometric	Higher curvature results to better jaw alignment and better roundness error
Self- alignment Of workpiece	Dynamic	Clamping force, moment arm, friction and angle of workpiece tilt as the factor on self-alignment
Selection of Locating surface	N/a	Clamping surface needs to be avoided For the clamping of workpiece with high l/d ratio, cylindrical surface should be considered
Non-symmetric deformation of jaw-workpiece	Geometric /dynamic	Caused by low rigidity of jaw-workpiece structure

• *Factors identified by this study*

The earlier studies [5,6,7] attributed the centering error of jaws to the geometric deviation of chuck components. In addition to the geometric errors, the authors have recognized that the centering error of a workpiece is caused by the factors described in Table 2.

Table 2 Summary of characteristics of factors affecting chucking error

Name of factor	Error type	Description of error
Jaw alignment error after jaw boring	Dynamic	Tilt or geometric deviation of boring plug causes the centering error in jaw alignment
Taper in jaw alignment	Dynamic	Higher clamping pressure with a chuck structure of lower rigidity can cause taper in jaw alignment.
Kinematic redundancy	Geometric	Mating of two imperfect parts (jaw and workpiece) can make the positioning of a workpiece non-repeatable.
Workpiece drop	Dynamic	Clamping of a long, heavy workpiece causes a workpiece drop in clamping.
Selection of locating surface	N/A	For the clamping of a long, heavy workpiece, a cylindrical surface needs to be used a locating surface.

2.3 Developing chucking error map

The factors discussed so far are summarized in Table 3, based on the stage of their occurrence in clamping. All the factors that occur in the same stage are listed in the same cell of the table.

Table 3 Factors affecting chucking error and their stages of influence

Stage of occurrence	Factors/errors affecting the eccentricity of chucked parts	Results
Preexisting Errors	▪ Deviation in shape of clamp transmission components ▪ Wear of clamp transmission component	Deviation in the radial displacement of individual jaws
Jaw boring	▪ Geometric error and tilt of jaw forming device ▪ Improper control of jaw boring pressure	Centering error and twist in the alignment of jaws after jaw boring Non-optimal tapering in jaw alignment
Workpiece mounting	▪Kinematic redundancy, selection of locating face ▪ Workpiece Geometric Error, tapering in jaw alignment	Non-repeatable mating of workpiece and jaws Centering error of mounted workpiece
Jaw clamping	▪Workpiece Drop ▪Jaw-Workpiece Deformation, • Self-Alignment of Workpiece	Centering error of chucked workpiece

A chucking error map was created, based on the results of error budgeting, as illustrated in Figure 3. To show the relation between these factors effectively, the error components that best represented the potential chucking error at each stage of clamping were defined as $\boldsymbol{e_i}$.

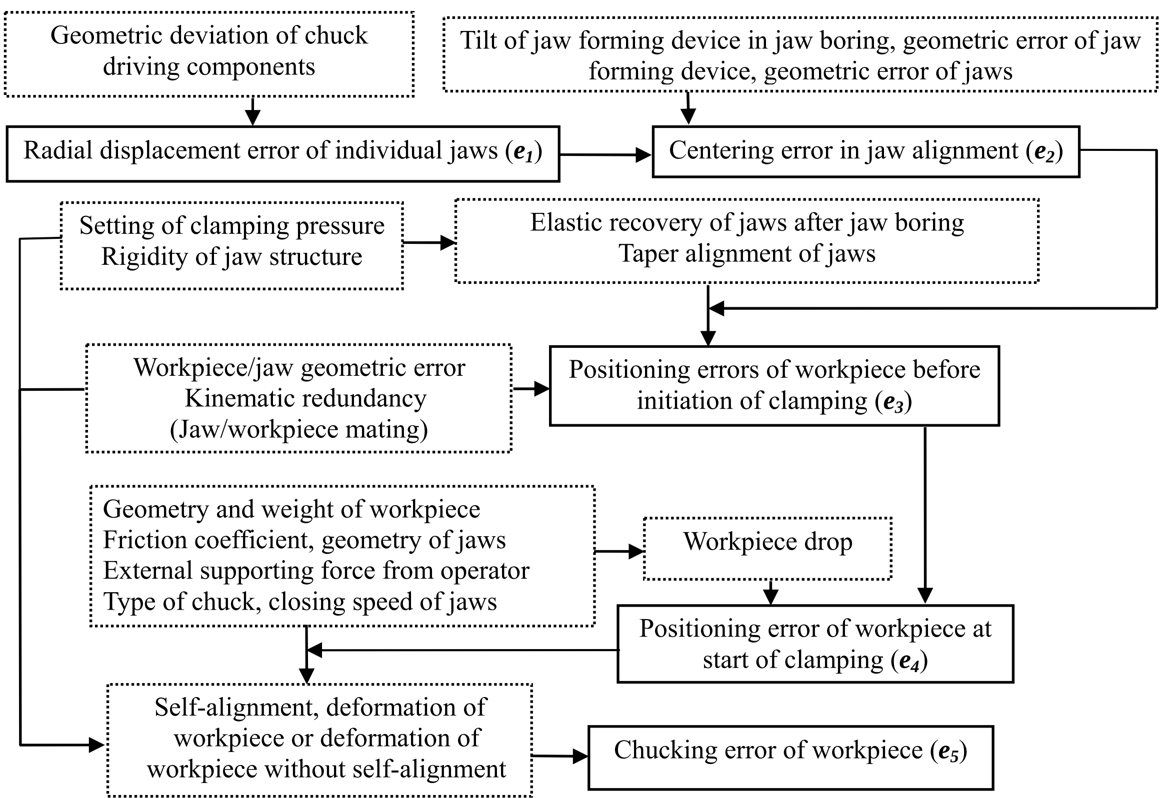


Fig. 2 Chucking error map

3 Developing Methods for Improving Chucking Accuracy

3.1 Methods for Minimizing Error Components in Chuckng

・ *Alignment error of jaws after jaw boring operation*

As shown in Table 3, two factors affect the positioning accuracy of the workpiece. The first one is the centering error in the alignment of jaws after jaw boring operation. The second is the excessive tapering in the alignment of jaws after jaw boring operation due to the inappropriate control of jaw clamping pressure [1]. Regarding the prevention of the tilt of the jaw forming device, an appropriate control of a clamping pressure is required to prevent the tapering of the surface on which the jaw forming device would be located. For example, a disk-shaped boring plug, which is used as a jaw forming device in most of the jaw boring operations, is located in a plug hole to withstand the clamping pressure during the boring operation of jaws. If the plug hole has a taper when it contacts to the 3 plug-hole surfaces, the disk would sit with a tilt since it will first contact with the bottom surfaces of a plug hole due to the inappropriate control of the clamping pressure. As an alternative, the use of a sphere-shaped disk plug can prevent the tilt of the plug by removing kinematic redundancy [1]. Another way to minimize the tapering in the jaw alignment is to raise the rigidity of the jaw structure by installing lager jaws if the situation permits. When lowering the clamping pressure in order to minimize the tapering in the alignment of jaws, clamping stability should be taken into consideration to prevent chatter in the machining.

・ *Non-repeatability in positioning of workpiece due to kinematic redundancy*

In chucking, a workpiece that has a certain degree of geometric deviations is clamped by geometrically imperfect jaws with different matching orientations at each time of clamping. Under the conditions in which a cylindrical surface should be used as a major locator due to the higher length to diameter ratio of a workpiece, the final position of the workpiece becomes non-repeatable (kinematically redundant). Due to friction, the original position of the workpiece, which is far from optimal, would not be recovered in most cases once it is established at the time of mounting. In this case, an appropriate reduction of the contact area is required to make the positioning of the workpiece more repeatable and accurate. When a flat surface is used as a major locating surface, the non-repeatability in the positioning of a chucked workpiece can be minimized by arranging 3 point contact between the jaws and the workpiece unless there is no workpiece drop during clamping. However, the accuracy in the positioning of chucking is not improved significantly since it is mainly determined by other factors [1].

・ *Chucking instability in form of workpiece drop*

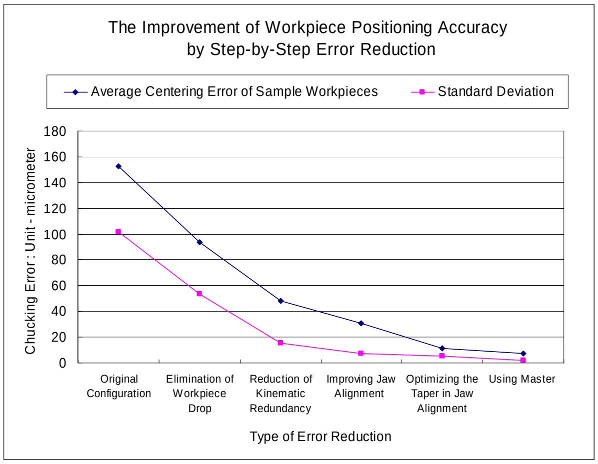
In the chucking of a workpiece with a horizontal chuck spindle, gravity is not in favor of stabilizing the position of the chucked workpiece. According to the experiment, "workpiece drop" was observed in the clamping of a workpiece with 13.5 Kg weight and the ratio of $\mathbf{L_w/D_w}$ as 0.75. As the weight and the $\mathbf{L_w/D_w}$ increased, the instability increased to a point at which the support of a human operator cannot completely cover this instability. According to other works of the author [1], this drop increased as the weight and $\mathbf{L_w/D_w}$ increased. The $\mathbf{l_c/L_w}$ ratio should be high enough to prevent the drop of the workpiece in the clamping of this type of workpieces. However, a greater contact area increases the non-repeatability of the chucked workpiece. Therefore, efforts to minimize the kinematic redundancy should be made to improve the accuracy and repeatability of the chucked workpiece. As $\mathbf{l_c/L_w}$ increases, an appropriate attention should be paid on the change of actual major locating surface.

• Positioning error of workpiece due to inappropriate selection of locating surface

Two different types of surfaces can be used as a major locating surface in the clamping of a cylindrical surface, depending on the geometry and the weight of the workpiece. They are a flat surface (end face) or a cylindrical surface (OD/ID). If the length to diameter ratio of the workpiece is high, a cylindrical surface should be considered as a major locating surface to prevent the drop of the workpiece. Otherwise, a flat surface should be used to avoid all the problems of error propagation, as commented by Hocken *et al*.[6]. The more criteria and guidelines on the selection of a major locating surface are available in the other work of the authors. If there is no changeover, the use of a special chuck, which can support a pull-back operation, can be considered for the clamping of workpieces with a higher length to diameter ratio [1].

3.2 Experimental Verification

The methods based on the results of earlier works were tested using the outer rings of a taper-roller bearing. We have demonstrated that the methods could minimize the influence of these factors on the accuracy and the repeatability of the positioning of the chucked workpiece very effectively as shown in Figure 3a and 3b.



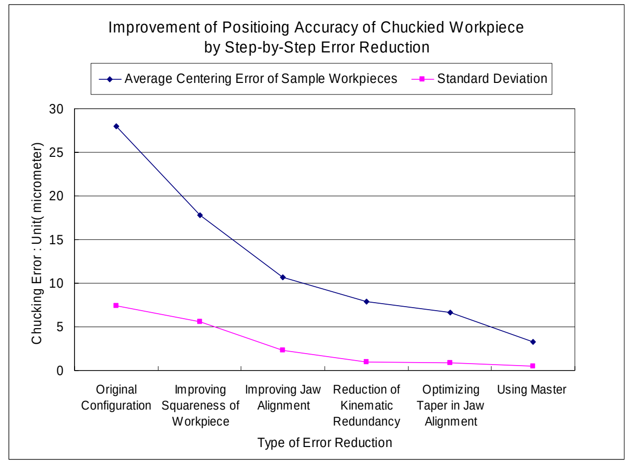


Fig.3a. The reduction results of chucking error by step-by-step approach for Workpiece Type I (OD surface as a major locating surface; length to diameter ratio 0.8, average weight 15.5 Kg).

Fig. 3b. The reduction results of chucking error by step-by-step approach for Workpiece Type II (End face as a major locating surface; length to diameter ratio 0.5, average weight 0.95 Kg).

4 Conclusions

In this work, factors that affect the chucking accuracy and repeatability of a cylindrical workpiece were identified. The characteristics of these factors and their effects on chucking errors were studied. From the result, a chucking error map was constructed. Methods for minimizing chucking error were developed, based on the earlier results. The methods were tested using the outer rings of a taper-roller bearing. We have demonstrated that the methods could minimize the influence of these factors on the accuracy and the repeatability of the positioning of the chucked workpiece very effectively. For the cases studied, we have achieved about 20 times improvement in chucking accuracy and 30 times in repeatability. The methods developed in this study can be applied to improve the accuracy and the repeatability of tools and parts.

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