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Paper:

On-Machine Estimation of Workholding State for Thin-Walled Parts

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The objective of this research is to investigate an on-machine estimation method to achieve efficient and fast estimation of the fixturing force and workpiece deformation. The estimation enables us to visualize workholding states and improves machining accuracies of thin-walled parts. In this research, a systematic estimation method of workholding states which combines fixturing simulation and locally measured strain is proposed and evaluated. The proposed on-machine estimation method is evaluated in different workholding conditions (clamping sequences and fixturing forces). Estimated fixturing force and workpiece deformation for a clamped thin-walled workpiece were compared to the results from the engineering experiments. From the comparison, it becomes clear that the proposed method has the feasibility to detect improper workholding states such as insufficient fixturing force or excessive deformation.

Keywords: machining accuracy, on-machine shape estimation, FEM analysis, workholding state, thin-walled parts

1. Introduction

In the development of modern manufacturing, the machining process is becoming more and more accurate. Fixtures are important components of the machining system which with machine tools and cutting tools are called the three major elements of workpiece processing [1]. The main function of the fixture is to position, restrain, and support the workpiece during the machining operation. The function is achieved by rationally arranging the positions of the fixturing devices (clamps and support blocks) and loading the appropriate fixturing force.

In precision machining, specialized dedicated fixtures are designed in most cases to avoid process variations during workholding [2]. However, different degrees of the workpiece deformation often occur during the actual machining process [3]. The clamping accuracy of the workpiece on the machine tool is an important factor that heavily affects machining accuracy. According to statistics, 20%–60% of the machining errors are caused by the clamping of the workpiece [4]. Especially in the aeronautical and aerospace industries, the typical parts are mostly large-size, weakly rigid thin-walled parts such as integral beams, frames, ribs, and engine blades [5, 6]. The problem of clamping deformation is more prominent, which strongly affects the performance, machining accuracy, and surface quality of the workpiece.

Due to the higher structure efficiency and lightweight characteristic, thin-walled parts are widely used in the modern manufacturing industry. However, from another point of view, these parts are complex in structure, weak stiffness, and high precision demand. During the machining process, because of low rigidity structural characteristics, elastic deformation is heavily affected by the workpiece-fixture interaction. Moreover, most of the fixturing process is executed as manual operations, which generate large process variations. These fluctuated fixturing processes have deteriorated machining accuracy for a long time. With the deep research of many scholars on thin-walled parts processing, great progress has been made in thin-walled parts clamping technology, machining simulation, and machining deformation error optimization [7]. At present, the method predicting the clamping deformation of thin-walled parts based on the finite element method (FEM) has become increasingly mature [8–11]. Many researches have studied the impact of clamping layout, fixturing force loading position, and loading sequence [12–14]. However, there are still some deficiencies in the above research; at present, the research on the clamping technology of thin-walled parts, cutting simulation, and optimization technology mainly focuses on the research of regular thin-walled parts, such as thin-walled frame parts and thin-walled plates. There are very few studies on the machining of complex curved-walls parts.

For this reason, this research aims to deal with thin-walled complex-shaped parts as the research object. Moreover, to improve machining accuracy with the use of general fixtures for clamping in small-lot production, we are focusing on the estimation of workpiece deformation and fixturing force at actual machining situations. Despite the energetic research mentioned above, an on-site evaluation of the actual workholding operation has been investigated by limited researchers [10]. Considering losses of machining failure, an estimation of actual workholding

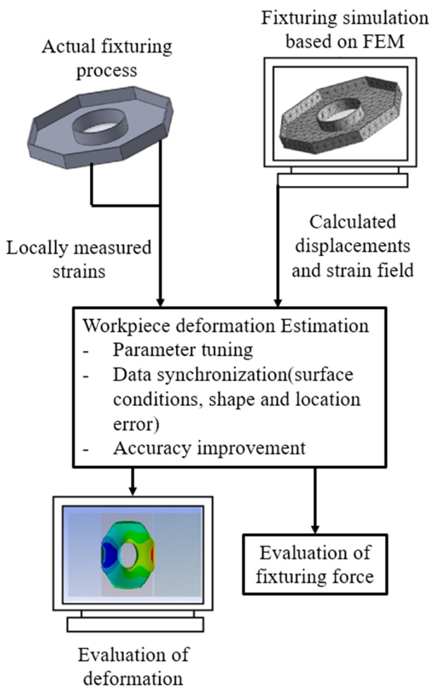


Fig. 1. Framework for on-machine estimation.

states is important to achieve precision machining.

To secure appropriate workholding, an estimation of the actual fixturing situation is necessary. Therefore, an on-machine estimation method for workholding situation has been proposed [10]. Because strain information of parts can be measured easily and less affected by parts location error, a concept of hybrid estimation method which combines FEM analysis and local strain measurement as illustrated **Fig. 1** has been investigated [10, 15–17]. However, the proposed method has a drawback for requiring preliminary preparation for state estimation. This drawback is manifested in that too many preliminary preparations will consume more time, which is not suitable to practical on-site application. Furthermore, the estimation concept has been confirmed with only deformations of simple workpiece shapes. To apply the method to the actual machining situation [18], it is necessary to develop a new estimation method that requires less preparation and can evaluate both force and deformation [19]. Furthermore, the applicability of the method must be evaluated with realistic evaluations by employing practical workholding devices with complicated workpieces.

2. Estimation Method

2.1. Hybrid Estimation Process of Workpiece State

We have proposed a method to estimate a workholding state by using simplified elastic analyses [20]. To simulate the solid contact of the fixturing process for actual workholding situations, it is necessary to introduce a general simulation technique applicable to various workpiece shapes and materials [21].

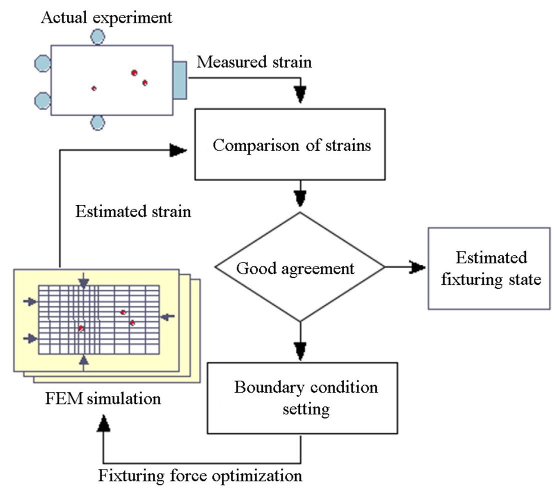


Fig. 2. Estimation flow of simple workholding state.

To estimate the workholding state from measured strains, the inverse problem of FEM analysis of workholding process should be solved with locally measured strain. In the standard elastic analysis, boundary conditions can determine workpiece deformation. Therefore, identification of appropriate boundary conditions leads to a better estimation of workholding process. In this research, a general mathematical programming method is introduced to estimate the boundary conditions of FEM analysis that can generate similar strains to measured strains. In the previous method [22], boundary conditions for FEM analysis must be decomposed into several simplified conditions. Although this preparation enables fast estimation, this preliminary preparation takes time and estimation accuracy is dependent on the appropriateness of the decomposition.

Therefore, a direct application of the optimization method is employed for state estimation. In principle, the strain can represent the deformation of the workpiece if plastic deformation does not occur in workholding process. Therefore, the deformation amount is different when the boundary conditions are not close to the actual clamping situation [23, 24]. In this research, a workholding state which indicates a set of fixturing force and workpiece deformation is estimated by minimizing the difference between measured strains and estimated strains. If the strain results (estimated and measured) show enough good agreement, then the fixturing force and estimated deformation can be considered as appropriate. Otherwise, the previous boundary conditions will be revised as new candidates of boundary conditions. This iteration loop is continued until the comparison results achieve enough good agreement. The analysis flow of workholding state estimation is illustrated in **Fig. 2**.

2.2. Procedures of Workholding State Estimation Under the Actual Fixturing Situation

From the viewpoint of manual operation task, the fixturing process can be defined as following three steps.

1. Placing the locators for workpiece positioning.
2. Aligning the workpiece to the locators.
3. Loading the fixturing force through the clamping devices.

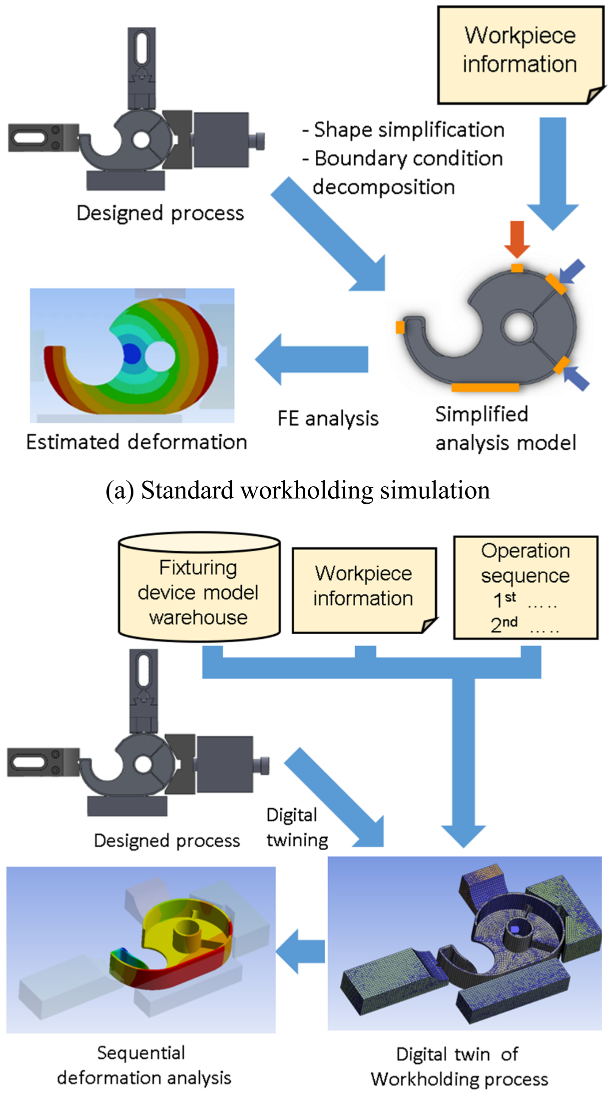
To achieve accurate fixturing, all these steps should be completed accurately. However, manual operations can generate the following errors.

I. Location error of locators.
II. Alignment error of workpiece.
III. Location error of clamping device.
IV. Excessive or insufficient loading force.
V. Wrong order of loading sequence.

Regarding the error of I–III, operators utilize a dial-gauge or a touch probe to confirm the actual location of the objects. These assessments can be involved in manual operation easily because standard machine tools are controlled based on geometrical coordination. On the other hand, evaluation and control of errors IV and V require external equipment or procedure because they are related to physical phenomena which cannot measure directly. Moreover, it is necessary to evaluate the direct effects of operation errors I–V to generate appropriate adjustment protocols for the human operator. Therefore, the representation of workholding state should correspond to manual operation.

In the standard simulation model of workholding, simplified boundary conditions are employed to reduce the calculation cost, eliminate modeling task of fixturing device, and improve the numerical stability as illustrated in **Fig. 3(a)**. As mentioned above, actual workholding operations are proceeded by controlling fixturing devices. Therefore, it is necessary to involve the models of fixturing devices in fixturing simulation as illustrated in **Fig. 3(b)**. Regarding the difficulties to employ the simplified boundary conditions, the recent computational environment enables us to calculate as-is problem. The recent common understanding of digital twin makes it possible to utilize models of various fixturing devices, and advanced FEM software improved the numerical robustness of calculations.

By introducing the fixturing device model into workholding process simulation, a task-level description of manual operation can be integrated into a process model as illustrated in **Fig. 4**. Based on the process model, the influence of errors IV and V can be estimated from the measured strain.



(a) Standard workholding simulation

(b) Digital twinned workholding simulation

Fig. 3. Workholding simulation framework.

2.3. Estimation Process of the Workholding State

As a standard formulation for the estimation of workholding process, an optimization procedure for minimizing the residual which represents the degree of similarity between calculation values and measured values is introduced. To apply the optimization procedure to multi-object and multi-step workholding analyses, connectivity to commercial FEM software is an important feature. Therefore, general optimization methods are more suitable than the customized optimization method such as accelerated estimation procedure by using decomposed elastic analysis [10].

Figure 4 represents an estimation flow for complex workholding states such as multi-object and multi-step workholding. In comparison with the case of simple workholding state as illustrated in **Fig. 2**, consideration of model construction process and clamping sequence becomes more important. By using a predefined fixturing device model with the contact model, direct correspondence between the process model and actual workholding situation can be obtained. Moreover, representations of loading sequence enable us to consider the variations of different loading sequences.

For the iterative search of appropriate loading forces

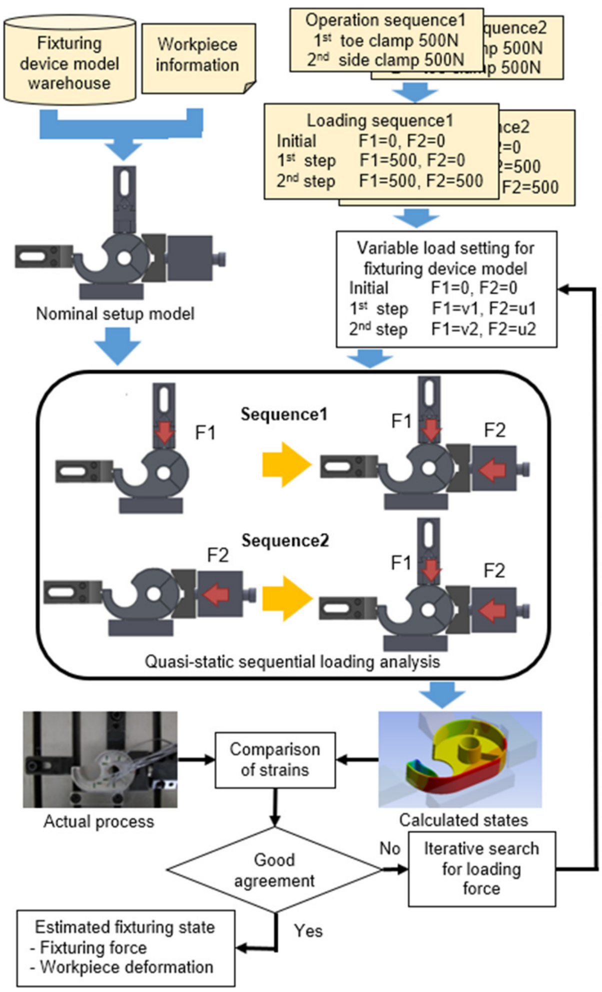


Fig. 4. Estimation flow of complex workholding state.

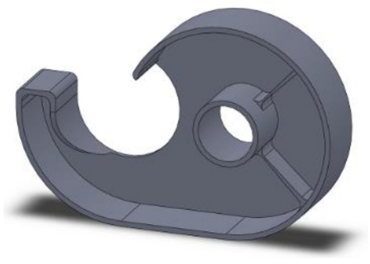


Fig. 5. Shape of thin-walled parts.

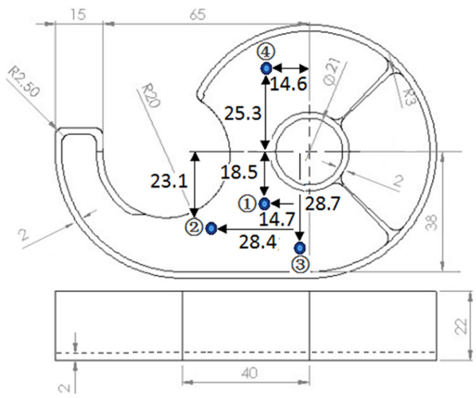


Fig. 6. Location of strain measurement points.

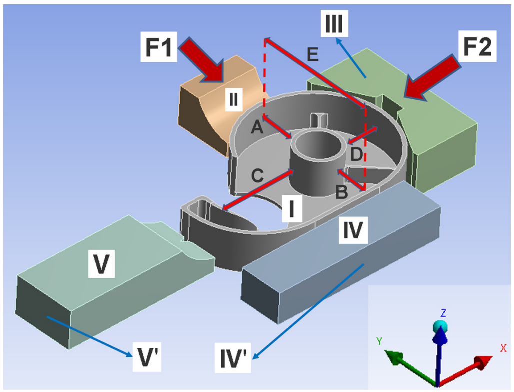
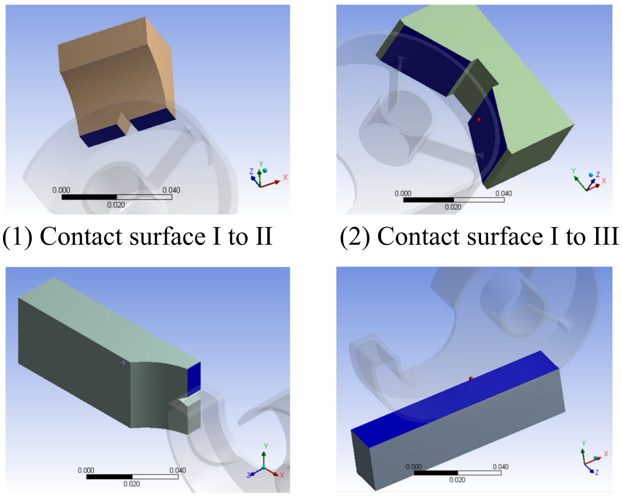


Fig. 7. Workholding setup and deformation measured position.

which generate similar strain distribution to the actual experiment, a general optimization procedure is connected to the multi-object and multi-step FEM analysis. Different loading sequences are applied to the fixturing process model and the similarity of strain distribution can be evaluated by calculating the similarity of representative points strains.

3. Experiment and Simulation of Example Workholding Problem

To confirm the effect of clamping sequences, workholding simulation considering the difference of clamping sequences was evaluated. FEM analysis of thin-walled workpiece with two-step clamping sequences is evaluated. In this case, a complicated shape of thin-walled parts is employed as a case study. The shape of parts is illustrated in **Fig. 5**. Strain gauges glued at evaluation points in **Fig. 6** were employed to measure the strains in workholding experiment. Because of the limitation of strain measurement equipment, four points of strains were utilized. The locations of strain measurement are determined by considering magnitude of strain and sensitivity to change in boundary conditions from the workholding simulation. This heuristic determination should be improved more systematically in practical situation. This is an important future task of this research. **Fig. 7** illustrates workholding method and measured dimensions (A)–(E) for deformation evaluation. The workpiece (I) attached with strain gauges is placed on the plane locator (IV) and toe locator (V). Controlled fixturing force by torque wrench is loaded through toe clamp (II) and side clamp (III). Contact surfaces of workpiece and workholding instruments are shown in **Fig. 8**. To simulate this workholding process, boundary conditions are set as listed in **Table 1**. Contact parts materials of workholding instruments are steel and stain-



(1) Contact surface I to II
(2) Contact surface I to III
(3) Contact surface I to IV
(4) Contact surface I to V

Fig. 8. Contact surfaces of workpiece and workholding instruments.

Table 1. Boundary conditions for analysis.

Relationship	**Model / Boundary condition**
Workpiece I	Elastic body (Aluminum alloy A2017)
Workholding instruments II III IV V	Rigid body
Fixturing force [N] (F1 and F2)	500 200
Friction coefficient	0.1
Mesh element size [mm]	2
II	Move only in the Y-axis direction
III	Move only in the X-axis direction
IV' and V' (Back surfaces of IV and V)	Fixed
Contact surface I-II	Solid contact with friction (Friction coefficient 0.1)
Contact surface I-III	Solid contact with friction (Friction coefficient 0.1)
Contact surface I-IV	Solid contact with friction (Friction coefficient 0.1)

less steel. Usually, the friction coefficients of aluminum alloy to steels or stainless steels vary depending on the surface roughness and surface cleanness. The values of coefficients between aluminum and steels vary from 0.45 to 0.02 depending on the roughness, lubrication, and literature [25–28]. Considering actual fixturing situations, surfaces of the instruments are usually smooth and contact surfaces often adhere to mechanical oils. As the safe-side evaluation, we introduced the friction coefficient that was set as 0.1.

The actual workholding experiment scene is shown in **Fig. 9**. For actual workholding experiments, the fixturing force must be adjustable. The fixturing forces of the clamps were adjusted by the screw torque. The relationship between the magnitude of the torque and the magnitude of the fixturing force generated was measured as preliminary experiments [29].

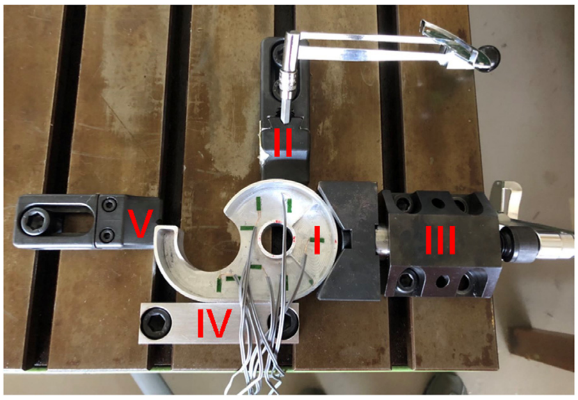


Fig. 9. Actual fixturing experiment setup.

Table 2. Fixture force sequence setting.

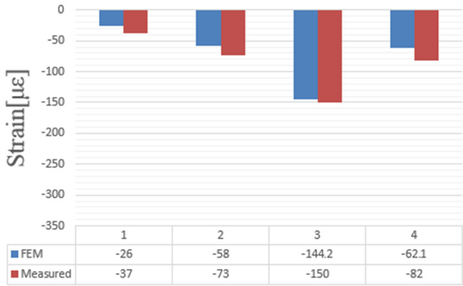
	Clamping sequence/force[N]	
Sequence 1	F1 (first)	F2 (second)
Step 1	500	1
Step 2	500	200
Sequence 2	F1 (second)	F2 (first)
Step 1	1	200
Step 2	500	200

For load measurement in preliminary experiment, experiment to calibrate the relations between loading forces and torque was carried out by using a compact compression type load cell-manufactured from Kyowa Electric Industry Co., Ltd. For measurement, loading and unloading were repeated with load cell-attached, loading-unloading were repeated measurements 10 times in one measurement set, 5 sets were repeated after removing load cell, and reinstalling was 50 times in total.

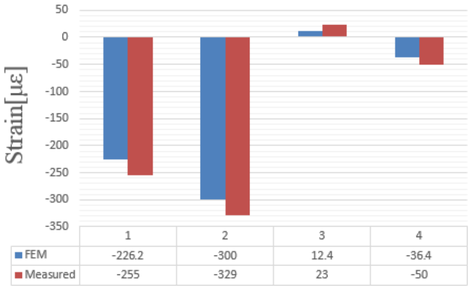
To simulate the sequential workholding process, quasi-static sequential boundary conditions were set as listed in **Tables 1** and **2**. For example, the load is set to $F_1 = 500$ N as the first fixturing force and $F_2 = 200$ N as the second fixturing force as Sequence 1 in **Table 2**. By assuming the whole process is 2 steps, the fixturing forces at the initial step are $F_1 = F_2 = 0$ N.

The fixturing forces at the first step are set as $F_1 = 500$ N, $F_2 = 0$ N. Next, the fixturing forces at the second step are set as $F_1 = 500$ N, $F_2 = 200$ N. To consider the effect of first step displacement, a sufficiently small fixturing force must be set for numerical stability. Therefore, we set the fixturing forces in the first step as $F_1 = 500$ N, $F_2 = 1$ N for Sequence 1 and $F_1 = 1$ N, $F_2 = 200$ N for Sequence 2, respectively. The situations of these two clamping sequences are illustrated in **Fig. 4**.

To confirm the representation ability of FEM analysis, a FEM-based workholding simulation is carried out by using commercial FEM software to compare the results of workholding experiment. Deformations and strains

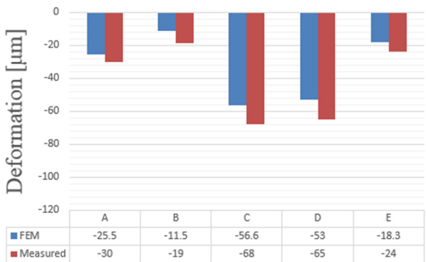


(a) Comparison of strains ① to ④ for Sequence 1

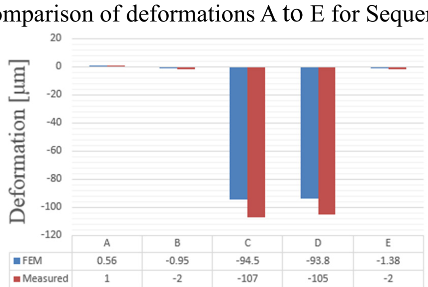


(b) Comparison of strains ① to ④ for Sequence 2

Fig. 10. Comparison of strains (FEM and measured).



(a) Comparison of deformations A to E for Sequence 1



(b) Comparison of deformations A to E for Sequence 2

Fig. 11. Comparison of deformations (FEM and measured).

of a workpiece under the workholding were estimated. The strain results after the whole clamping process which were measured by strain gauges are shown in **Fig. 10**. The results of the deformation comparison are shown in **Fig. 11**. Deformations were measured by digital micrometers and measured values were average values for 15 measurements.

Although analyzed strains and deformations show reasonable agreement (average difference is less than 24%), they tend to be smaller than measured values. Further investigation to confirm the appropriateness of workpiece rigidity such as identification of physical properties and/or mesh modeling is necessary to improve the estimation. From the aspect of feasibility study, the results show FEM analysis can calculate the realistic deformation field when appropriate boundary conditions are prepared.

The maximum deformation value of Sequence 1 is significantly smaller than that of Sequence 2, which means applying F_1 as the first fixturing force is better than F_2. Therefore, confirming the clamping sequence in an actual workholding situation is important to achieve precision machining of thin-walled parts.

4. Estimated Results of Workholding States

The assumed workholding process situation is the same as Section 3 illustrated in **Fig. 7**. F_1 and F_2 indicate fixturing forces applied by toe clamp and side clamp respectively. Evaluation functions of the optimization were set to the difference between the measured strains and calculated strains by FEM simulation. Workholding process situation shown in **Fig. 7** is investigated as the case study. To confirm the feasibility of the proposed estimation method, we investigate two fixture clamping sequences as listed in **Table 2**. In these cases, we assume machining sequence has been confirmed before the estimation. The estimation is used to confirm the appropriateness of the manual operation. Estimation of machining sequence is a future issue of this research. When the sequence estimation becomes possible, irregular cases can be detected from the local strain measurement.

Workpiece strains at pre-determined points were measured when the fixturing forces F_1 and F_2 were set for each machining sequence. From the measured strains and FEM model of the workpiece, fixturing forces were estimated to equalize the measured and calculated strains. In principle, the strain represents local information of deformation, therefore strains and deformations are expected to show a similar tendency.

The fixturing forces under these two sequences are estimated.

As the method for state estimation, the response surface method (RSM) is introduced [30, 31]. The mathematical optimization model which was introduced in Section 2.3 is used as the optimization method. Concerning the optimization settings, we select response surface type as standard response surface-full 2nd order polynomials. To reduce the effect of a priori knowledge, the search range of fixturing force was set to range from 1 to 1000 N. Based on considering the strain results obtained from the actual experiment, the fixturing force was optimized and the estimated fixturing forces setting plan was obtained through state estimation. Controlled forces at experiment (nominal force) and estimated forces are shown in **Fig. 12**. The average deviation rates of force estimation for all estimations are smaller than 10%.

To evaluate the estimated deformation, corresponding workpiece deformations (dimensions A–E in **Fig. 7**) calculated from estimated fixturing forces of Sequences 1

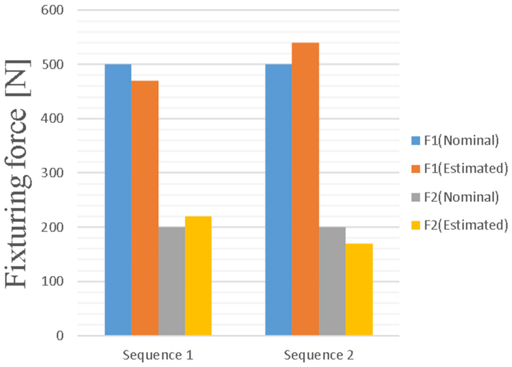
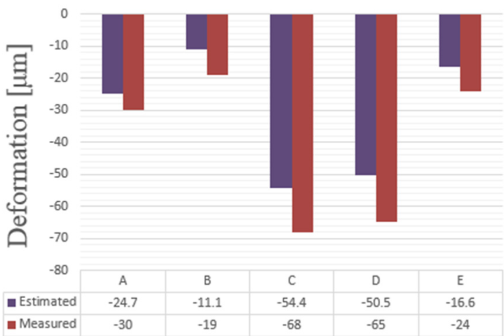
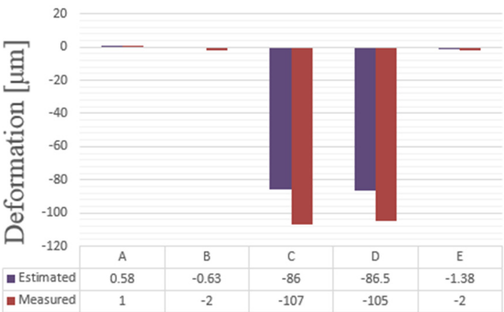


Fig. 12. Estimated result of fixturing forces.



(a) Comparison of Sequence 1



(b) Comparison of Sequence 2

Fig. 13. Comparison of deformations (estimated and measured).

and 2 are obtained. Comparisons of estimated deformation and measured deformation are shown in **Fig. 13**. The estimated results show similar tendency to the simulation results (**Fig. 11**). From these results, the estimated deformations with the iterative optimization algorithm are smaller than the measured deformations and the average difference is about 22%. This indicates the proposed method has a possibility to detect the difference of different workholding situations from the measured strains.

5. Conclusions

To achieve an on-machine estimation of workholding situation considering fixture clamping sequence, an estimation flow of complex workholding states is proposed. As an evaluation of the proposed estimation method, estimation of fixturing force and deformation is experimentally investigated. The results indicate the proposed method can estimate the workholding situation of the thin-walled parts under different fixture sequences.

A systematic method to determine the measurement points is also an important research topic to be solved. This is an important future task of this research. Moreover, the applicability of the method will be confirmed by utilizing non-contact strain measurement.

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