薄肉部品の精密加工のための工作物保持状態の機上推定

Doctoral Dissertation:

On-machine Estimation of Workholding State for Precision Machining of Thin-walled Parts

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Doctoral dissertation

On-machine Estimation of Workholding State for Precision Machining of Thin-walled Parts

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Abstract

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, have weak stiffness, and high precision demand. During the machining process, because of low rigidity structural characteristics, actual workholding process and fixture selection are heavily affected by the deformation of thin-walled parts. 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.

The objective of this research is to investigate an on-machine estimation method to achieve an efficient and fast estimation of the fixturing force and workpiece deformation. The estimation enables visualization of 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 was 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.

In this thesis, several methods are used to build a system to estimate the workholding state of thin-walled parts in the machining process. The main story is described as follows.

Firstly, trends of recent production are summarized as a background of this research. Roles of thin-walled parts which apply in the modern manufacturing industry, trends of thin-walled workpiece machining, and the importance of thin-walled workpieces are introduced. Moreover, related researches about workholding state estimation in workholding situations, measurement technology development, FEM analysis, and a combination of measurement and simulation are surveyed.

Secondly, to concretely explain the overall objective, the whole research process is illustrated to follow four steps:

(1) Feasibility verification of On-machine estimation

(2) Fixturing force estimation

(3) Effect of clamping sequence

(4) Measurement points selection

Thirdly, a framework for on-machine estimation is proposed. Based on considerations of process variables, a concept of the iteration optimization process, workholding simulation framework, estimation flow of complex

workholding state, and evaluation criterion of measurable points are explained. This research presents these methods to build an effective system of thin-walled parts workholding estimation.

Fourthly, several case studies are set to verify our proposal based on the four steps of the objective paragraph. From the results of case studies, the proposed estimation method of workholding state can visualize the fixturing states in various workholding situation.

Lastly, the conclusion of the dissertation is described.

Key words: Machining accuracy, On-machine shape estimation, FEM analysis, Workholding state, Thin-walled parts

Outline

Chapter 1
Introduction

1.1 Background

1.1.1 Applications of thin-walled parts

Aerospace manufacturing is the most important component of the national equipment manufacturing industry and plays an important role in the national economy. With the rapid development of science and new technologies, international competition has become increasingly fierce. The aerospace industry has become an important symbol for measuring the technological innovation capability, the modernization of the national defense scientific research industry, and the comprehensive strength of the national manufacturing industry in the world [1,2]. At the same time, the performance puts forward higher requirements on aircraft and spacecraft. In the aerospace manufacturing industry, large number of thin-walled parts, such as aircraft integral siding, bulkheads, girders were shown in Figure 1-1. From the view of thin-walled parts structural design, to improve the carrying capacity of aircraft and longer flying distance, the weight should be reduced as much as possible to improve the overall structural strength [3-6].

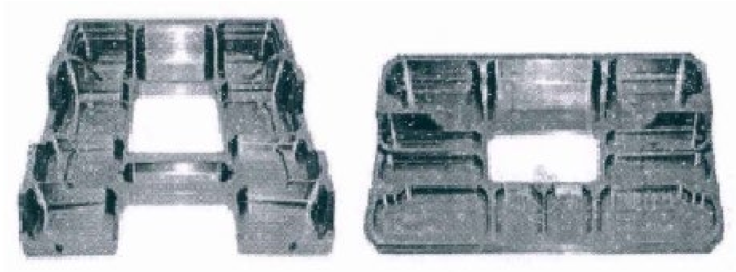


Fig.1-1 Typical aircraft thin-walled parts [7]

1.1.2 The importance of fixtures

The official definition of thin-walled parts is the ratio of the part wall thickness to the curvature (or outline size) radius of the inner diameter is smaller than 1:20.

The characteristics of conventional workpieces are:

(1) Rigid workpiece

(2) Large or medium batch

(3) Standard precision

(4) Simple shape

(5) Common material

Compared with conventional workpieces, the basic superiorities of the advanced workpiece are reflected in these five aspects:

(1) Low rigidity workpiece

(2) Small-lot batch

(3) Higher precision

(4) Complicated shape with thin-walled structure

(5) Higher performance material

Moreover, reduction of machining costs is eagerly desired because of competitive environment. Comparing to the researches on machining process, researches on workholding method have not been investigated.

Just as its name implies, the role of workholding is fixing the target partly by applying force during the machining process [8], and keeping the workpiece shape within allowable deformation to suppress the workpiece [9]. In this research, we are focusing on the following two items of workholding situation [10]. The first is fixturing conditions, second is workpiece deformation.

Due to the higher structure efficiency and lightweight characteristic, thin-walled parts are widely used in the modern manufacturing industry. From another point of view, these parts are complex in structure, have weak stiffness, high-precision demand, and are easy to distort [11-15]. During the machining process, their material properties and structural characteristics, the action of local elastic deformation in the machining process, fixture clamping selection will heavy affect the deformation of the thin-walled workpiece. This deformation problem has been plagued the aerospace industry.

Usually, fixture design and manufacture can account for 10%–20% of the total cost of a manufacturing system, approximately 40% of rejected thin-walled parts are due to dimensioning errors that are attributed to poor fixturing design [16-20]. It is necessary to design a reliable workholding method to reduce the thin-walled workpiece deformation and fixturing disturbance [21]. Aiming to utilize general-purpose fixtures such as multi-points contact workholding locators, it has been studied the factors which cause deformation and then effectively reduce the distortion. We have proposed a hybrid on-machine estimation method [22-25]. Furthermore, FEM analysis and engineering experiments verification were compared to investigate the effect of clamping force magnitude and clamping sequence [26-28]. It was confirmed from these comparison results that the factors (Fixturing force, clamping sequence, strain, deformation) which we predict were acting on the fixture–workpiece system.

1.2 The introduction of workholding

Workholding is a process in which a workpiece acquires a correct machining position by fixture before machining. Positioning is to limit the degree of freedom. If a workpiece has not been positioned, the spatial position is uncertain with six degrees of freedom. It means the degree of freedom can move and rotation around with these three orthogonal coordinate axes of x, y, and z. Therefore, if we want to generate a fully positioned workpiece, it is necessary to eliminate these six degrees of freedom. Usually, six support points (positioning locators) are used to limit the six degrees of freedom of the workpiece, each of which limits a corresponding degree of freedom [29-31].

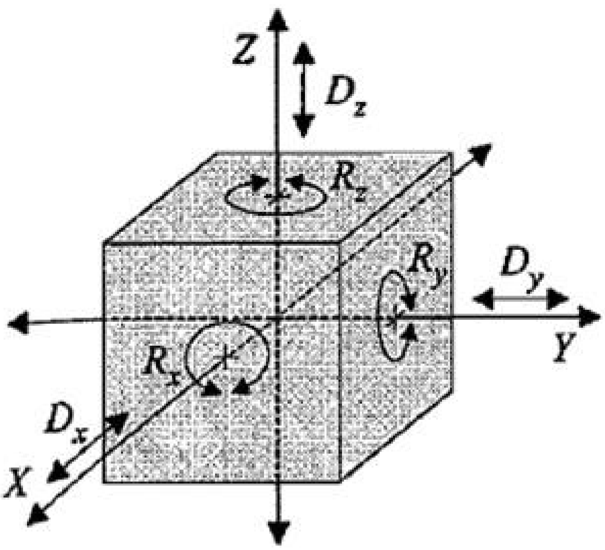


Fig.1-2 Six degrees of freedom [31]

The six-point positioning principle applies to the positioning of any shape workpiece. If this principle is violated, the position of the workpiece in the fixture cannot be completely determined. However, when positioning with the six-point positioning principle of the workpiece, it must be flexibly used according to the specific processing requirements. The shape of the workpiece is different, the positioning surface is different, and the arrangement of the positioning points will be different. Generally speaking, the purpose is to use the simplest positioning method to make the workpiece Get the right position quickly in the fixture process.

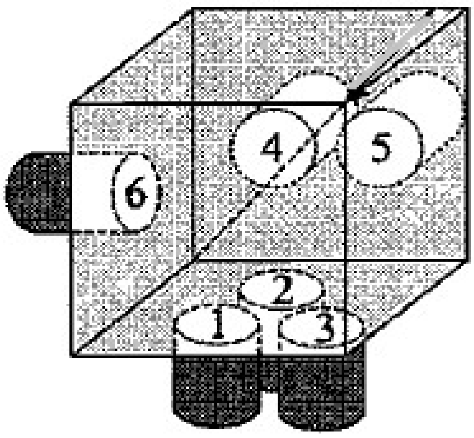


Fig.1-3 Six-point positioning principle [31]

Furthermore, the jigs used for workholding are divided into dedicated jigs and universal jigs. The dedicated jig is used for individual workpieces with stable and highly accurate gripping, but the cost and manufacturing time always become a problem. So, locator and clamp as universal jigs are widely used in the general workholding situation.

Generally, locators are always used for dimensions fixed and adjustable, being installed around or under the workpiece. Figure 1-4 shows the different types of locators that insert under the target part and adjusts the height of the work part.

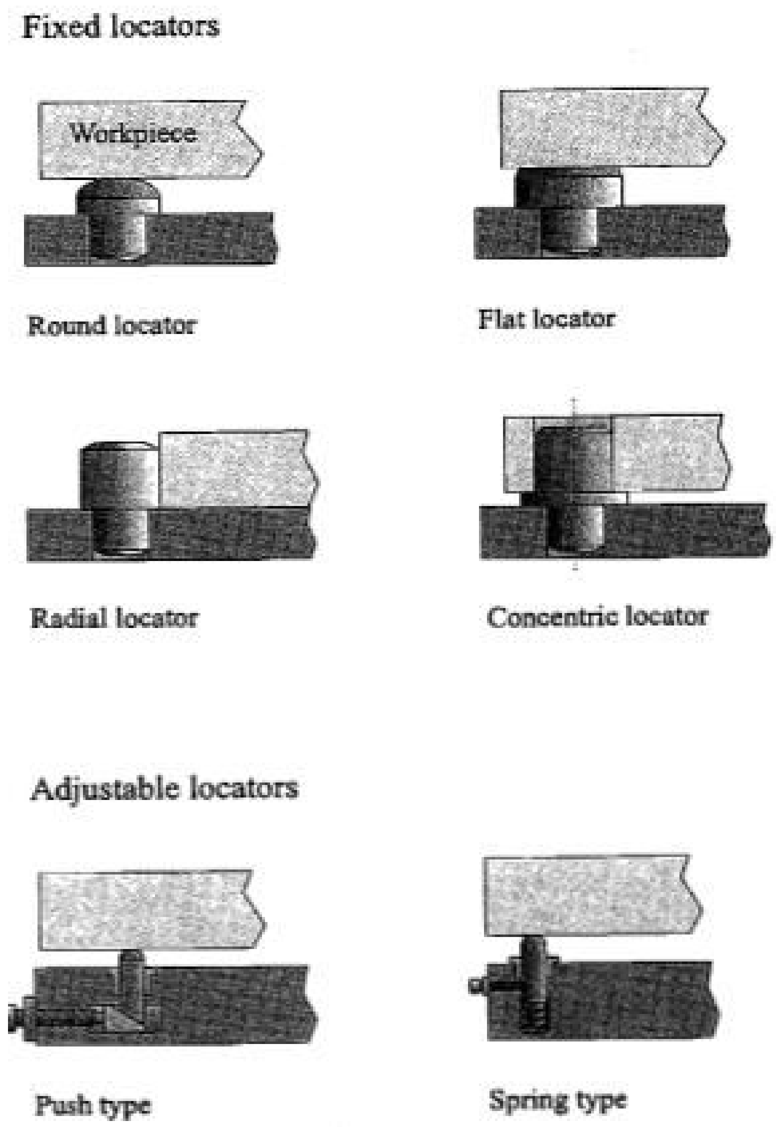


Fig.1-4 Type of locators [31]

The role of the clamp is to fix the workpiece under clamping force to the objective position. Due to the inappropriate clamping force will generate heavily plastic deformation, workpiece distortion, and damage such as breakage may occur, so attention must be paid.

The following things must be considered when determining the type of jig:

○ Condition at the time of contact

- Frequency of use
- Depending on conditions such as moving the jig manually or moving automatically
- Types of locators and clamps
- Locator position
- It is necessary to decide the value of the clamping force before the clamp was installed.

1.3 Small-lot manufacturing

During the cold war, the nuclear weapons complex produced thousands of components each year to support the stockpile. The manufacturing process stream had high production capacity but not always high yields. Through Fig.1-5 A qualified process and what can go wrong(b) outlines problems that can arise when one tries to develop a qualified process with lots that are down. To solve a series of blind points in the dynamic process that was poorly understood and not monitored, in-process monitoring and control became essential to small-lot manufacturing [32]. Which we must employ the date reduction methods to find the key signatures that might identify the presence of specific faults, then we should use those signatures to develop learning algorithms that only identify the faults but also classify their causes.

(a)

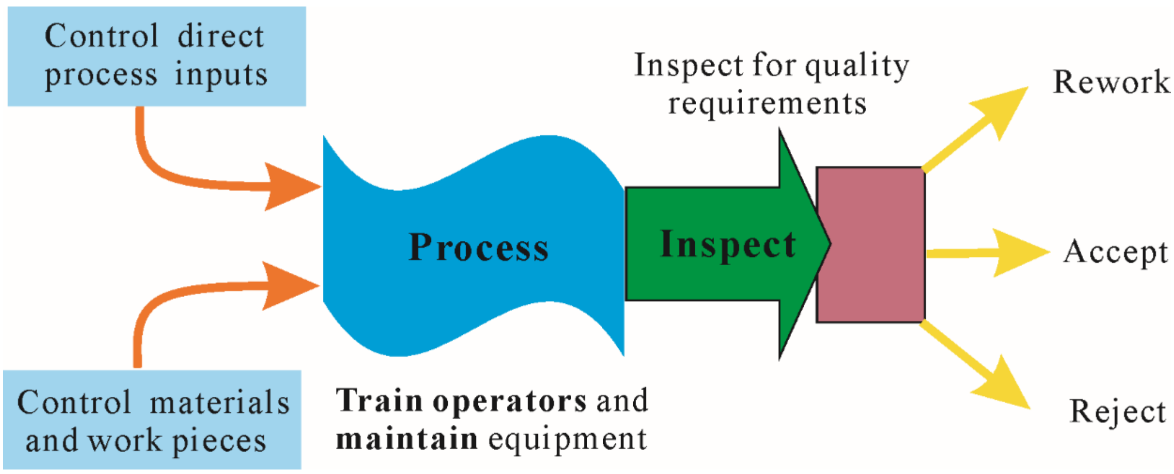


Fig.1-5 A qualified process and what can go wrong

(b)

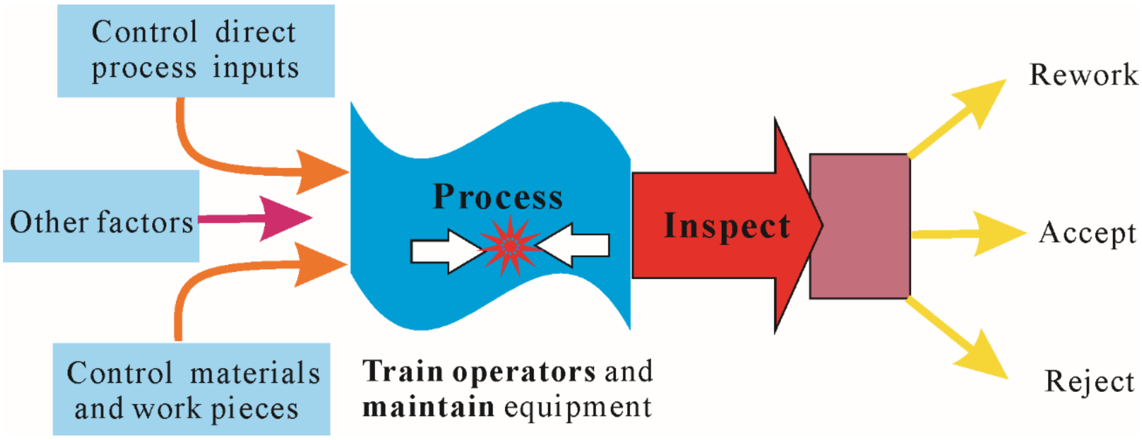


Fig.1-5 A qualified process and what can go wrong(cont.)

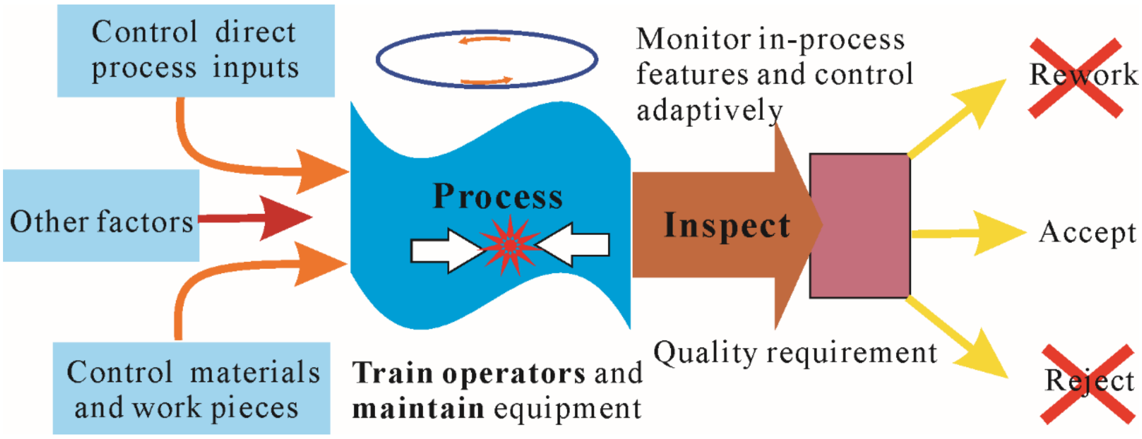


Fig.1-6 In-process monitoring and control [33]

In recent years, there are increasing demands for small lot production technologies to deal with diversifying needs and rapid forming tool production technologies to survive in global competition on the development of new products. The sheet metal forming technique requires the rapid production of tooling which is essential in the forming process.

1.4 Simulations applied in the machining process

Finite element (FE) simulation of machining can be used as a replacement or a supplementary to the conventional experiment allowing an analysis to be performed at a lower cost. With the rapid development of computer technology and the theory of numerical analysis, finite element simulation is more and more widely used in machining. Many commercial finite element software such as Abaqus, Advantedge, Deform, Ls-Dyna, and so on have become powerful tools for metal machining simulation.

The finite element method (FEM) has been employed to solve static contact models, experimental and analytical methods have been developed to estimate the values of strain and deformation in static contact [34]. Reduce energy consumption for both cost-saving and environmental friendliness. With the rapid use of internet and simulation software, it is significant to know that simulation has played a much important role in the industry. From kinds of literature, there are many research papers written about the application of simulation in the machining process, not only thin-workpiece deformation prediction but also the application of thin-workpiece error control [35-36].

Analytical modeling, as opposed to the widely used FEM-based modeling, is much faster in computation time, there are provided several analytical and simulation approaches for static contact modeling in the workholding process. An analytical model for the prediction of workpiece deformation in thin-walled workholding process is developed.

In the field of manufacturing engineering, the computer simulation is one of the important results, these calculated models can obviously reduce or even eliminate the repeated experiments in the design of fixture, choosing type of workholding process, estimation workpiece deformation due to workholding to achieve precision and manageable machining.

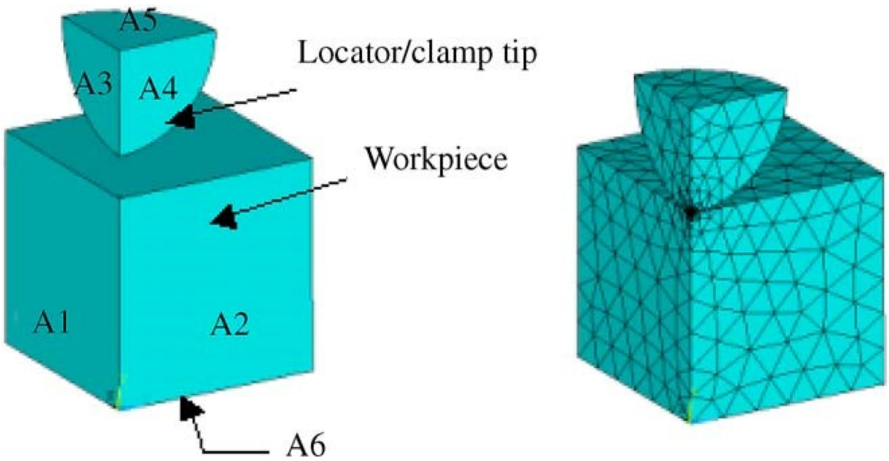


Fig.1-7 Finite element models of the workpiece and locator/clamp and their corresponding.[37]

1.5 The main contents of this thesis

In order to research on-machine estimation of workholding situation for precision machining of thin-walled parts, the following topics are discussed in this paper.

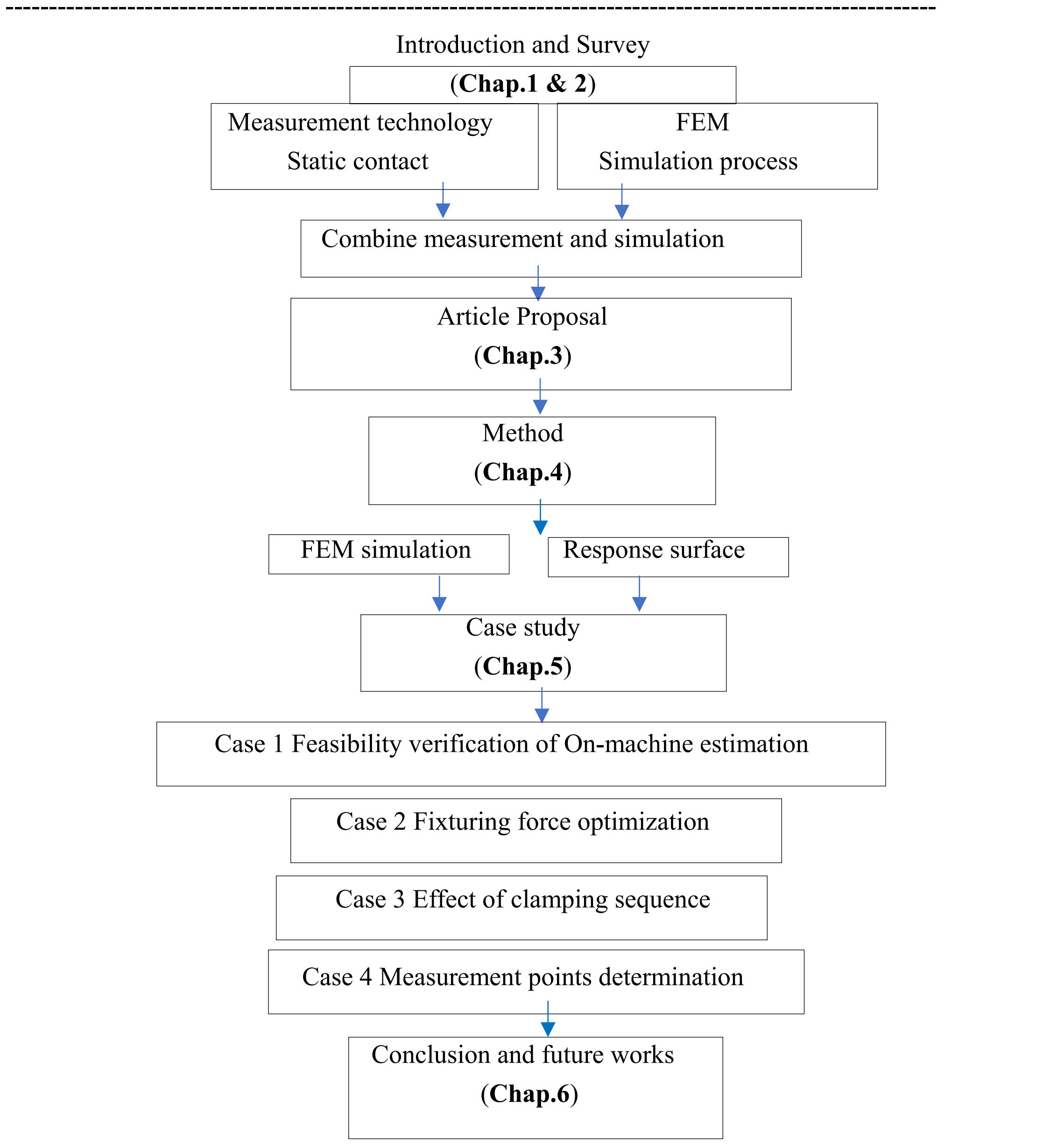


Fig.1-8 Organization of this thesis

Chapter 2
Survey of related research methods

2.1 Research summarizes

2.1.1 Summary of fixture design research

Various researches have been done because jigs designing is difficult. Therefore, in the following paper, we will review what kind of points these studies focus on.

○ Paper's title: A review and analysis of current computer-aided fixture design approaches

This paper was written by Iain Boyle,Yiming Rong,David C.Brown [37]. To respond effectively to this demand, manufacturers need to ensure that their manufacturing practices are sufficiently flexible to allow them to achieve rapid product development. Fixturing, which involves using fixtures to secure workpieces during machining so that they can be transformed into parts that meet required design specifications, is a significant contributing factor towards achieving manufacturing flexibility. To enable flexible fixturing, considerable levels of research effort have been devoted to supporting the process of fixture design through the development of computer-aided fixture design (CAFD) tools and approaches. This paper contains a review of these research efforts. Over seventy-five CAFD tools and approaches are reviewed in terms of the fixture design phases they support and the underlying technology upon which they are based. The primary conclusion of the review is that while significant advances have been made in supporting fixture design, there are primarily two research issues that require further effort. The first of these is that current CAFD research is segmented in nature and there remains a need to provide more cohesive fixture design support. Secondly, a greater focus is required on supporting the detailed design of a fixture's physical structure.

Table2-1 . Necessary conditions of jig design [37]

Generic requirement	Abstract sub-requirement examples
Physical	• The fixture must be physically capable of accommodating the workpiece geometry and weight. • The fixture must allow access to the workpiece features to be machined.
Tolerance	•The fixture locating tolerances should be sufficient to satisfy part design tolerances.
Constraining	•The fixture shall ensure workpiece stability (i.e., ensure that workpiece force and moment equilibrium are maintained). • The fixture shall ensure that the fixture/workpiece stiffness is sufficient to prevent deformation from occurring that could result in design tolerances not being achieved.
Affordability	•The fixture cost shall not exceed desired levels. • The fixture assembly/disassembly times shall not exceed desired levels. •The fixture operation time shall not exceed desired levels.
Collision prevention	•The fixture shall not cause toolpath–fixture collisions to occur. •The fixture shall cause workpiece–fixture collisions to occur (other than at the designated locating and clamping positions). •The fixture shall not cause fixture–fixture collisions to occur (other than at the designated fixture component connection points).

Usability	•The fixture weight shall not exceed desired levels. •The fixture shall not cause surface damage at the workpiece/fixture interface. •The fixture shall provide tool guidance to designated workpiece features. •The fixture shall ensure error-proofing (i.e., the fixture should prevent incorrect insertion of the workpiece into the fixture). •The fixture shall facilitate chip shedding (i.e., the fixture should provide a means for allowing machined chips to flow away from the workpiece and fixture).

2.1.2 Proposal of the workholding method for thin-walled parts

Workholding method of the thin-walled workpiece has become a big problem, so numerous studies have been done in practice. In the following papers, studies have been made to reduce the amount of deformation by adsorption as a method for mounting thin-walled workpieces.

○ Paper's title: Assessment of photo-activated adhesive workholding (PAW) technology for holding “hard-to-hold” workpieces for machining

This paper was written by De Meter, E. and Santhosh Kumar, J [38].

Aim to research the grasping of graspable workpiece parts using photosensitive adhesives called Photo Activation Work Holding (PAW) technology. Manufacturers often have to machine “hard-to-hold” metallic workpieces using conventional fixturing. Manufacturers often have to machine “hard-to-hold” metallic workpieces using conventional fixturing.

In these special cases, machined feature quality typically suffers from set-up-related errors, or set-up lead time suffers from the extra time necessary to check and correct for them. A technology that may alleviate both problems is photo-activated workholding (PAW) technology. This paper describes an investigation in which a photo-activated workholding (PAW) technology solution was created to hold a ‘‘hard-to-hold’’ bracket casting for low volume machining at a contract manufacturer. A comparison to the existing conventional solution revealed that the PAW technology yielded substantially better-machined feature quality, machining lead time, and machining cost.

About PAW technology, a photocurable structural adhesive is applied to the tip of a pin of a jig of Fig.2-1. The workpiece and the light-curable structural adhesive are cured and bonded by applying light. Compared with the existing grasping method, the PAW technology reduced the positioning tolerance and reduced the processing lead time.

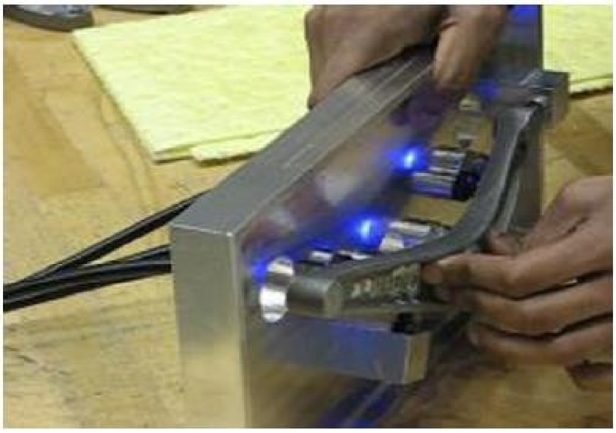


Fig.2-1 Illustration of the photo-curing process used to bond the bracket casting to the PAW fixture [36]

Fig.2-2 PAW fixture and bracket casting mounted in the vise for the Op #10 machining processes [36]

2.1.3 Related research of workholding simulation

In this section, we introduce the research which verified the factor of deformation by comparing the actual workholding result with the static FEM simulation.

○ Paper's title: Finite element modeling of fixture–workpiece contacts: single contact modeling and experimental verification

This paper was written by S. Satyanarayana and Shreyes N. Melkote Santhosh Kumar [39].

The determination of machined surface error necessitates a thorough understanding of the fixture–workpiece system's reaction forces and elastic deformation. Because it can readily account for multiple sources of compliance in the system, the finite element method (FEM) is ideally suited for estimating workpiece elastic deformation and reaction forces.

○ Paper's title: Prediction of workpiece deformation in a fixture system using the finite element method

This paper was writ by Shane P. Siebenaler and Shreyes N. Melkote [40].

The distortion of the workpiece due to clamping force will have a significant impact on the thin-walled workpiece's quality. As consequence, the results of finite element analysis utilizing ANSYS® Version 5.7. Analysis software to dynamically model the gripping tool and the workpiece parts and estimate the workpiece parts' deformation are presented in this study.

Figure 2-3 depicted the targeted sections in this study, and Figure 2-4 depicted the equipment. The researchers employed finite element analysis (FEA) to construct a fixture-workpiece system and investigate the effect of fixture body compliance on workpiece deformation. Furthermore, the impact of specific finite element model parameters on prediction accuracy is investigated. The workpiece deformation and locator response forces predicted by the FEA model were verified experimentally and found to be within 5% of the experimental data. It was discovered that modeling simply the workpiece and fixture contact points captures 98 percent of total system compliance for the fixture–workpiece system studied in this study.

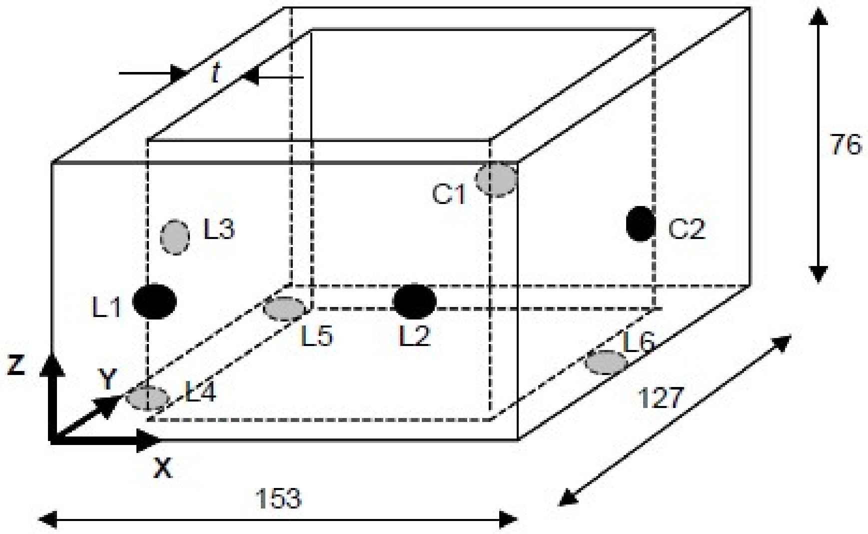


Fig.2-3 Targeted workholding workpiece [38]

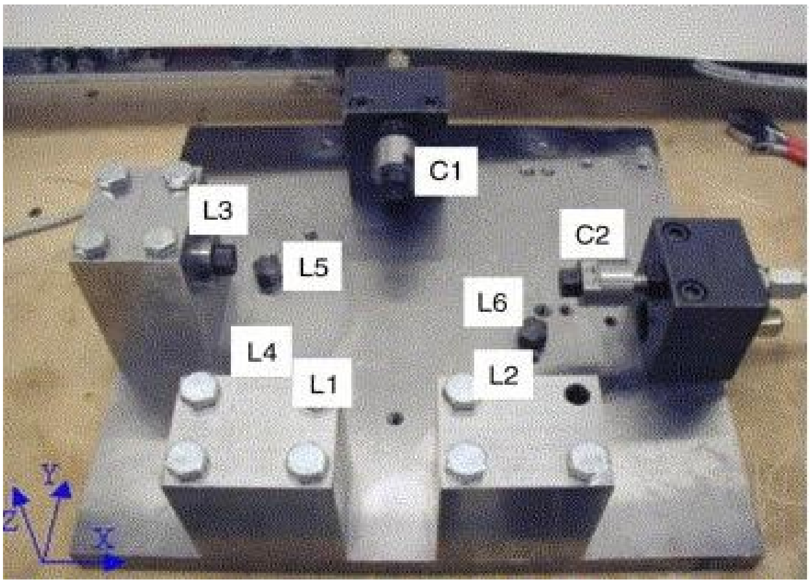


Fig.2-4 Actual workholding equipment [38]

This is summarized of related research so far, the research on the deformation of the workpiece needs to take into more realistic factors that may occur in the actual workholding situation. For now, there is no comprehensive consideration yet and more research is needed.

2.2 FEM used in manufacturing

To maximize the limited measuring points, this paper presents a method to evaluate the effectiveness of each measuring point from aspects of the stability of measurement and sensitivity to the process variation. As a quantification method of the effectiveness of the measuring point, a finite element method (FEM)–based static contact simulation is utilized [41].

In the 1940s, the rapid development of the aviation industry for area plane machine structure is put forward more and more high demand, the engineers had to in precise design and computing, at the same time plan for the development of computer technology makes use of numerical computing method to study the cutting process is possible. In the 50s ~ 60s with the finite element method (FEM) in the rapid development, limited to the early stage when the level of computer hardware and software and theory, the finite element numerical calculation method was not popular in engineering. But in the 60s ~ 70s, there was a large general-purpose finite element program, they were good at doing calculation precisely and reliability. in the following 40 years, a great number of scholars studies the basis of FEM [41,42].

At an early stage when the level of computer hardware and software and theory, the finite element numerical calculation method is not in the engineering. They gained popularity in 60 ~ 70s a large general-purpose finite element program, and they calculated precision and reliability.

Efficient computational efficiency became the analysis of the engineering structure calculation tools. In the later 40 years, scholars in a large amount of basic research. In 1973, Lee and Kobayashi of rigid-plastic finite element method (fem) are put forward for the first time Matrix column type, the extremely promoted the limited element numerical value simulation technology in the application in the process of metal volume into shape. In 1974, Tay. Stevenson and Davis for the first time by finite element method to calculate the orthogonal cutting tool, cutting, workpieces the temperature distribution. In the Year 1979, Mróz, Norris, and Zienkiewicz Put forward the sticky plastic material such as finite element formulations and viscoplasticity is deduced Finite element of penalty function method, the high temperature molding the analysis of the problem is resolved. In June 2006, The United States Net shape manufacturing engineering research center, Ohio state university Professor Altan and others at CIRP high-speed cutting meeting, at this stage of finite element simulation of high-speed cutting work made a detailed report and puts forward the future research.

2.3 Response surface optimization

Response Surface Methodology (RSM) is a method of obtaining data through experiments that use an acceptable experimental design strategy. To fit the functional connection between the components and the response values, the multivariate quadratic regression equation is utilized. A statistical strategy to tackle the multivariate problem is to analyze the regression equation to determine the best process parameters [43,44].

The experimental design and optimization approach both fail to provide an intuitive graph, making it hard to intuitively see the optimal point. Although the ideal value may be obtained, visual discrimination of the optimized region is challenging. The response surface analysis method (also known as the response surface method) was created as a result of this. Response surface analysis is an optimization approach that uses graphical tools to apply the response of the system (such as the strain distribution or deformation in the static contact) as a function of one or more elements (such as clamping force, friction coefficient, etc.). Figure 2-5 shows an illustration of a response surface. The relationship is displayed so that we can intuitively choose the best conditions for the experimental design.

To create such a response surface and analyze it to locate the good conditions or region, you must first create an appropriate mathematical model (modeling) based on a great number of measurement test data, and then utilize that mathematical model to create a 3D coordinates image.

To establish the model in static contact measurement, the model parameters are determined using the least-squares approach. Following the modeling procedure, the two components are used to determine the X and Y coordinates. A three-dimensional surface of the Z coordinate is the corresponding response derived using the following formula (2-factor response surface).

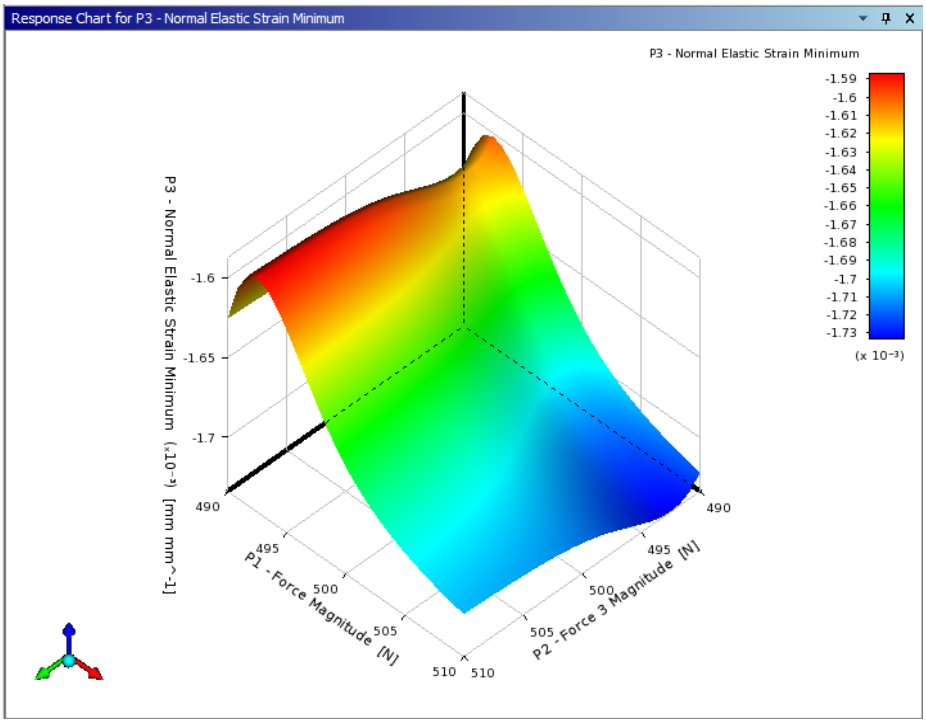


Fig.2-5 Response surface in static contact

2.4 Combine measurement and simulation

Small-batch, high quality and agile production methods have been required by most manufacturers. To achieve an accurate and reliable thin-walled workpiece machining process, it is necessary to understand workholding behavior in the machining process. As a result of rigidity improvements of modern machine tools, strain distribution and deformation of workpiece become an important phenomenon in precision machining. Many investigations have been reported to predict deformation influence in workholding process. Furthermore, methods to identify process parameters for static simulation are also discussed. On the other hand, a concept of model-based monitoring has been expected as an important technology for advanced machining, because the detailed understanding of workpiece state is considered as an effective method for machining process control. Based on these technological backgrounds, a method to estimate strain distribution of workpieces by combining workpiece measurement and deformation analysis has been proposed.

Workholding is a mild deformation process, the tool and the workpiece to withstand the constant mechanical load, the workholding process research also has the following problems:

(1) Determine the positioning, clamping error, and machining deformation control of thin-walled parts with contact and friction conditions.

The influence of the solid contact variable on the strain changing field and the distribution of the strain during the clamping situation is analyzed, with a focus on the friction, sliding, and deformation behaviors of the workpiece under different contact and friction conditions, using a FEM simulation based on the characteristics of thin-walled parts with low rigidity and easy deformation. The experimental and finite element simulation analysis methods were used to construct a fixture contact model [45].

(2) Determination of measurable points

According to orthogonal test design by variable (friction coefficient, clamping force, etc.) and variable value range, measured points location formula of clamping situation property has built. Based on the results of the calculation, measurable points for different machining situations are evaluated.

(3) Research on selection and optimization of fixture scheme

Exploring the mechanism of the sensitive measurable points' machining deformation and clamping error caused by the fixture process. Predicting the overall structure of the workpiece's strain and deformation to identify the way to establish the positioning components, judge and pick the right workpiece clamping method under various clamping situations, creating the basis for how to apply the best fixture scheme layout.

Our laboratory has been studying thin-walled parts for a long time. Prof.

Teramoto gave an introduction about using strain to detect deformation in workholding process both by experiment and computer simulation. From the previous research of our group, we already had a clear illustration by combining experimental results and the simulation, the strain distribution on workpiece could be measured by confirmed parameters. Former year, Mr. Kutomi, who was in our group proposed a response surface by ANSYS workbench, which illustrated the accurate results did and based on all work done in these years. However, the variations of workholding method are generated by using the different combination of model parameters in the end milling process. Therefore, I am still looking for proposing a new method, which can summarize deformation change based on the method to select appropriate strain positions based on a variation conscious machining evaluation.

No matter in industries or automobiles adopted Computer-Aided Engineering (CAE) to decrease the number of trials of actual experiments, effective experimental mechanical tests are needed the validate CAE results, shown in Fig.2-6. In the previous research, the experimental setup and some of the experimental results. In this section, only the main points of the experiment described in detail in the mentioned research were outlined. We proposed an estimated method to detect strain and relative parameters by combining experimental results and simulation (show in Fig.2-7).

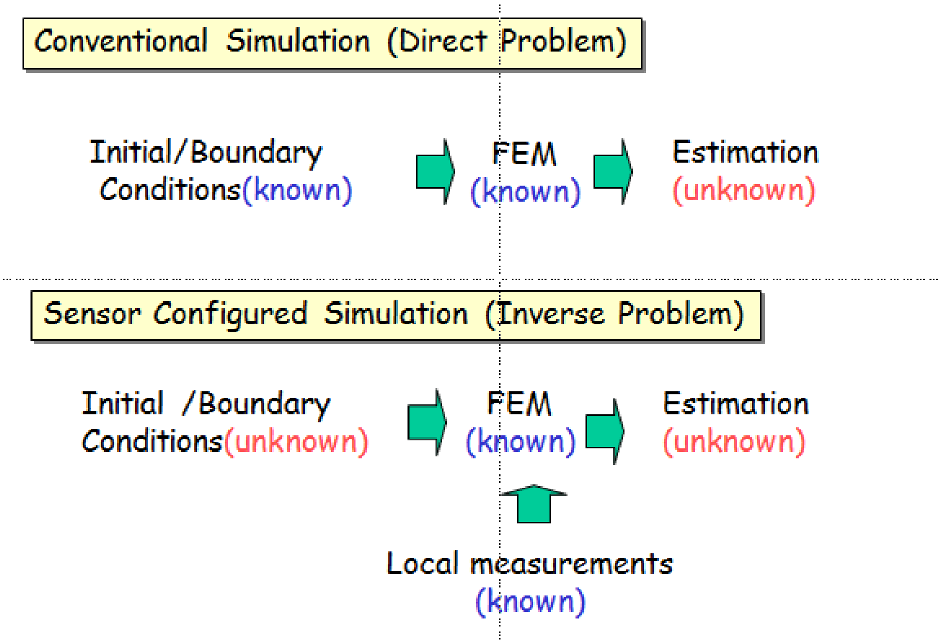


Fig.2-6 Comparison of conventional simulation and proposed Sensor-configured simulation

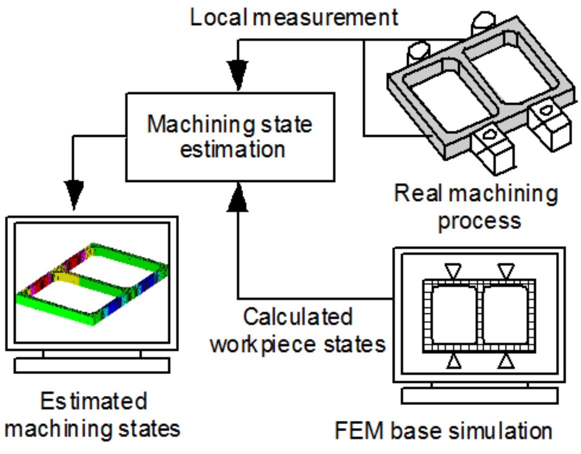


Fig.2-7 Combination of measurement and simulation

Chapter 3
Article Proposal

3.1 The proposal of this subject

The global competitive environment is quickly changing due to advanced manufacturing technologies. Companies and countries that move now to capture its potential will prosper in the twenty-first century.

Smart manufacturing will connect these islands, allowing data to flow freely across the facility. Plant-wide optimization and enterprise-wide management objectives will benefit from the convergence of machine-gathered data and human intelligence, including significant advances in economic performance, worker safety, and environmental sustainability. Smart manufacturing brings together information, technology, and human innovation to accelerate the creation and implementation of industrial intelligence across the board. It will transform the way items are designed, made, transported, and sold forever. By enabling zero-emission, zero-incident production, it will increase worker safety and safeguard the environment. It will aid in the preservation of employment in the United States by keeping manufacturing competitive in the global economy, despite the significantly greater cost of doing business elsewhere. Smart manufacturing will enhance plant edibility, cut product costs, and promote environmental sustainability. It will allow us to create cutting-edge new items made of next-generation materials.

However, completed parts from near net manufacturing must deal with issues such as complicated forms from end-milling, hard material from machining, and thin-walled components, and traditional experiments to overcome the effect of error from the deformation process are widely recognized in manufacturing. The typical challenge in machining components is how to make the simulation realistic, thus we're looking at the workholding process to forecast strain distribution in workholding situations to help with deformation estimate in thin-walled parts [46].

We suggested a method for calculating the strain of each observed spot on a thin-walled workpiece surface using simulations and actual measurements under more realistic boundary conditions. A finite element technique (FEM) based on static contact simulation is used as a way of quantifying the efficacy of the observed sites. The strain value of each measurable point is calculated using the findings of the nominal simulation and sensitivity analysis. Procedures for evaluation and examples of difficulties are also offered. The practicality of the proposed approach is proven by the example's findings.

In conventional workholding research, only assuming the ideal workholding situation such as, minimum fixturing equipment, ideal contact conditions, and nominal fixturing conditions simply apply to elastic FEM analysis. However, in actual workholding process, more realistic factors should be considered, for example: error caused by manual operation, overconstrained, variable contact conditions, and variable fixturing operation. If we hope the estimation result approach to the actual workholding result, then these factors are shown in Fig.3-1 must be considered seriously [47].

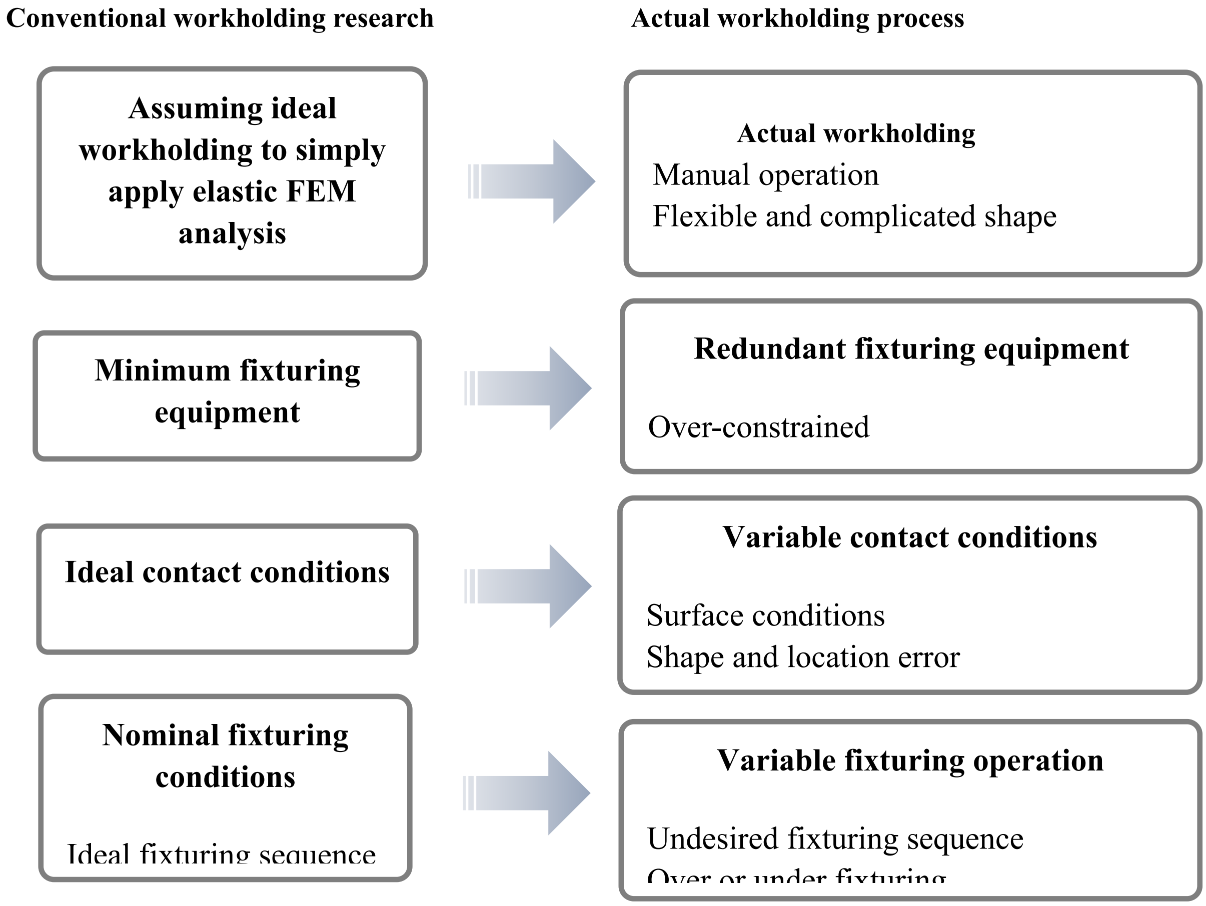


Fig.3-1 Comparison between conventional workholding research and actual workholding process

Normally, fixturing process steps by manual operation can be set 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

And the errors caused by manual operation could be divided into the following 5 types:

(1) Location error of locators

(2) Alignment error of workpiece

(3) Location error of clamping device

(4) Excessive or insufficient loading force

(5) Wrong order of loading sequence

Regarding the error of (1) to (3), 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, evaluating and controlling errors (4) and (5) require external equipment or procedure because they are hard to detect by geometry instruments directly. Moreover, it is necessary to evaluate the direct effects of operation errors (1) to (5) to generate appropriate adjustment protocols for the human operator. Therefore, the representation of workholding state should correspond to manual operation.

3.2 The technical route

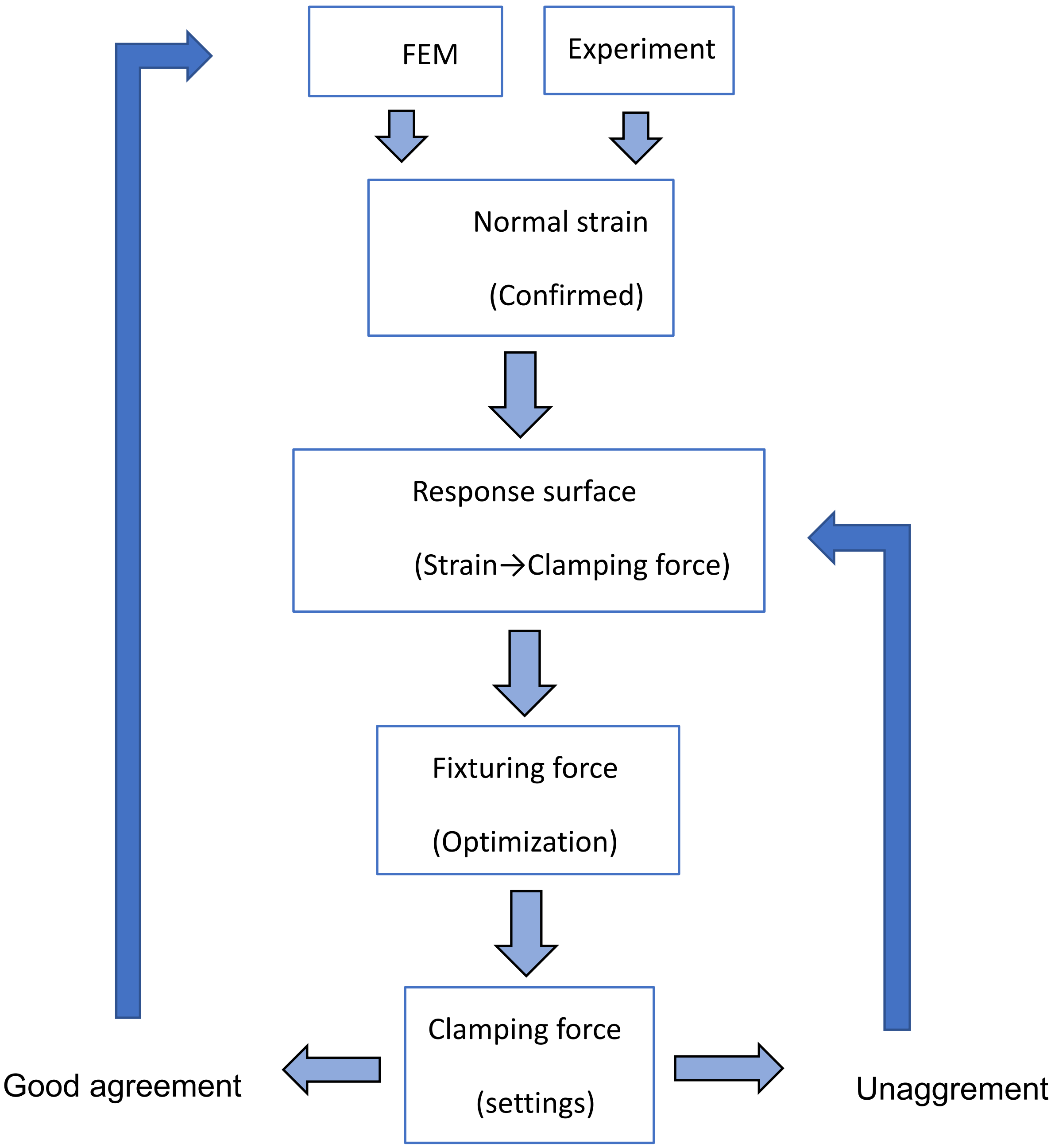


Fig.3-2 Framework of research technological process

The framework is based on combining locally measured information and FEM (Finite Element Method)-based process simulation. To evaluate performance of strain distribution in workholding process, we identify specific algebraic function and simulation, and give a new method to illustrate this method will impact manufacturing practices. Fig.3-2 describes how the methodology may be used as useful way to capture the current organizational state and its value is displayed and discussed through cases study of applying the methodology.

Chapter 4
Research methods

4.1 On-machine estimation

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 [48,49]. At present, the method predicting the clamping deformation of thin-walled parts based on the finite element method (FEM) has become increasingly mature [22-25]. Many researches have studied the impact of clamping layout, fixturing force loading position, loading sequence [26-28]. 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 [25]. Considering losses of machining failure, an estimation of actual workholding 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 [25]. 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 Fig4-1 has been investigated [25,50-52]. 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 for practical on-site application. Furthermore, the estimation concept has been confirmed with only deformations of simple workpieceshapes. To apply the method to the actual machining situation [53], it is necessary to develop a new estimation method that requires less preparation and can evaluate both force and deformation [54]. Furthermore, the method of applicability must be evaluated with realistic evaluations by employing practical workholding devices with complicated workpieces.

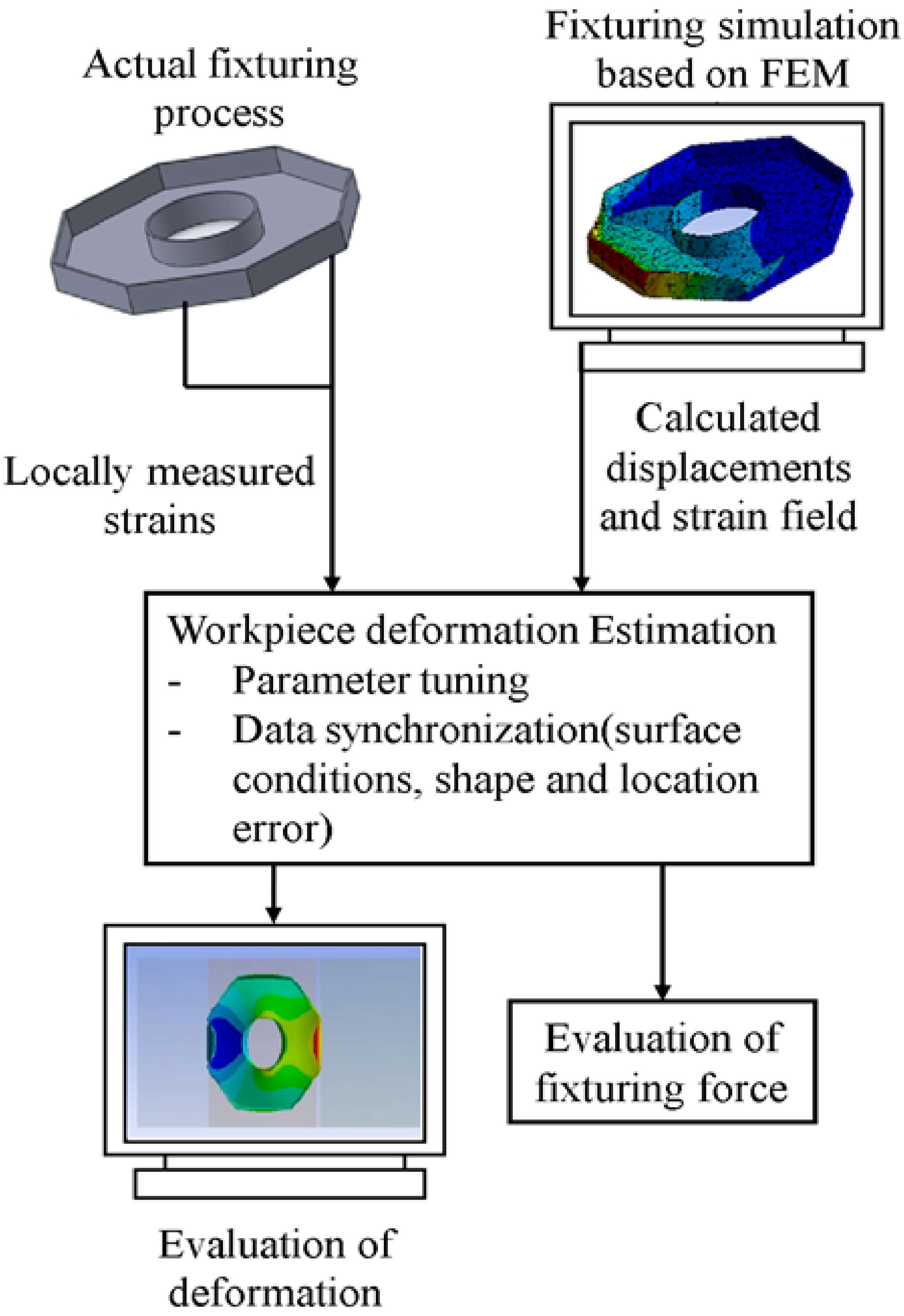


Fig.4-1 Framework for on-machine estimation

4.2 Estimation flow of simple workholding state

We have proposed a method to estimate a workholding state by using simplified elastic analyses [55]. 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 [56].

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, the 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 [57], 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 [58,59]. 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 the flow of workholding state estimation is illustrated in Fig.4-2.

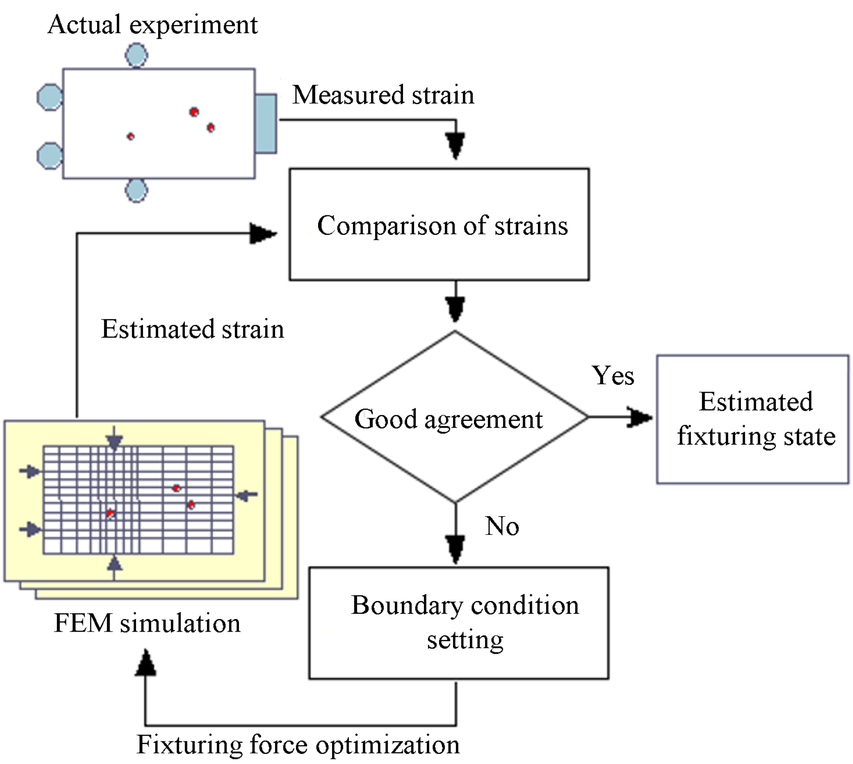
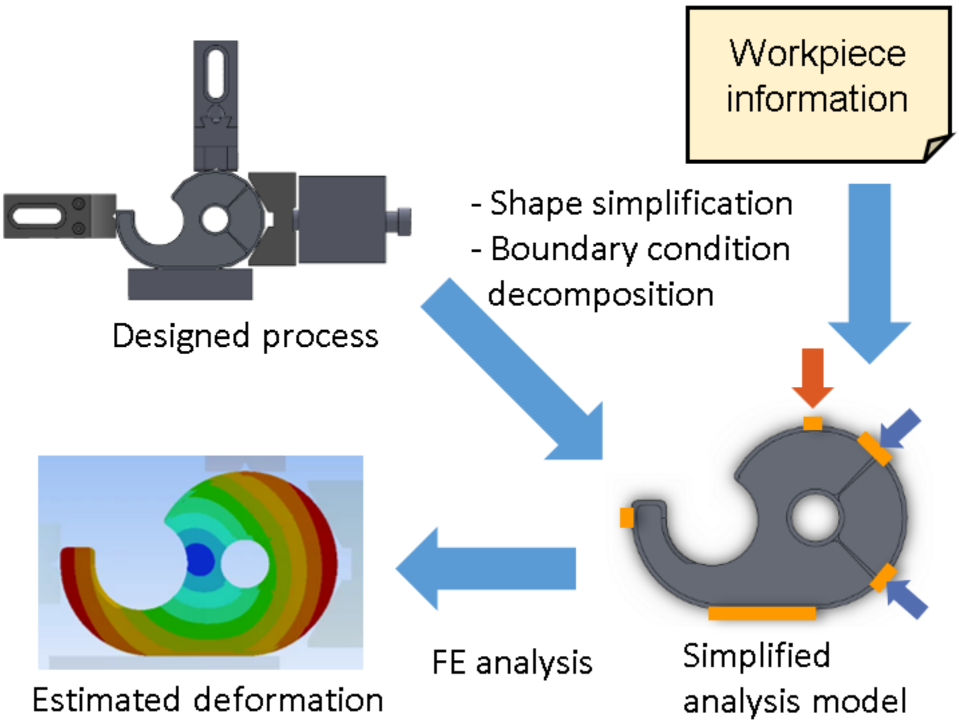


Fig. 4-2 Estimation flow of simple workholding state

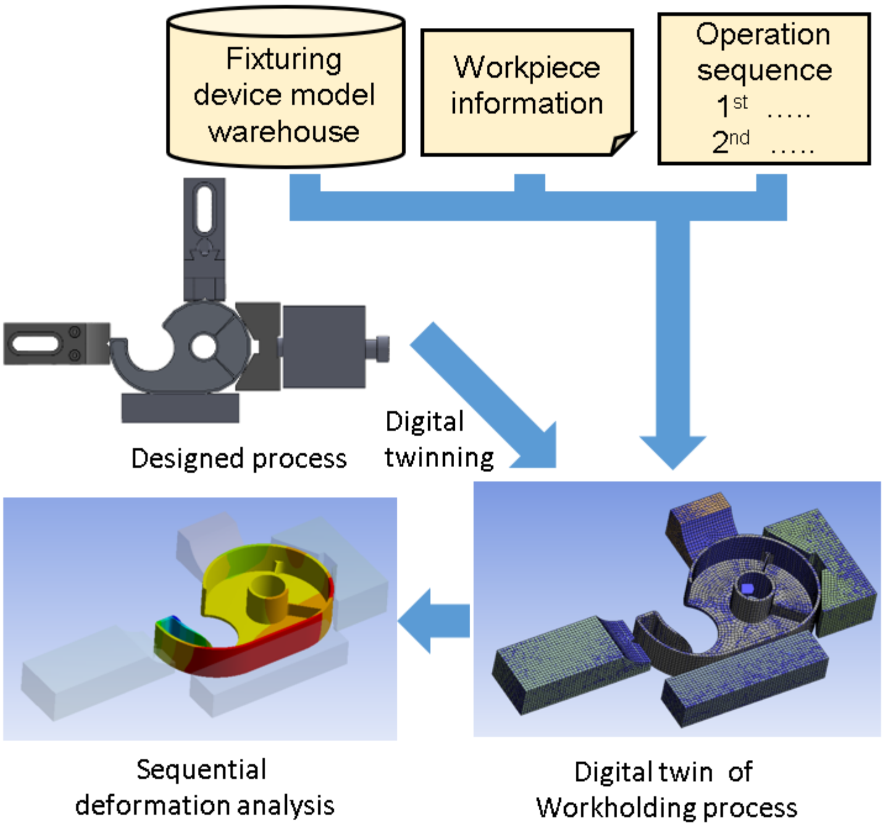
4.3 Hybrid estimation process of workpiece state

In the standard simulation model of workholding, simplified boundary conditions are employed to reduce the calculation cost, eliminate modeling task of the fixturing device, and improve the numerical stability as illustrated in Fig.4-3 (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.4-3 (b).



(a) Standard workholding simulation

Fig.4-3 Workholding simulation framework



(b) Digital twinned workholding simulation

Fig.4-3 Workholding simulation framework (cont.)

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.4-4. Based on the process model, the influence of errors IV and V can be estimated from the measured strain.

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-

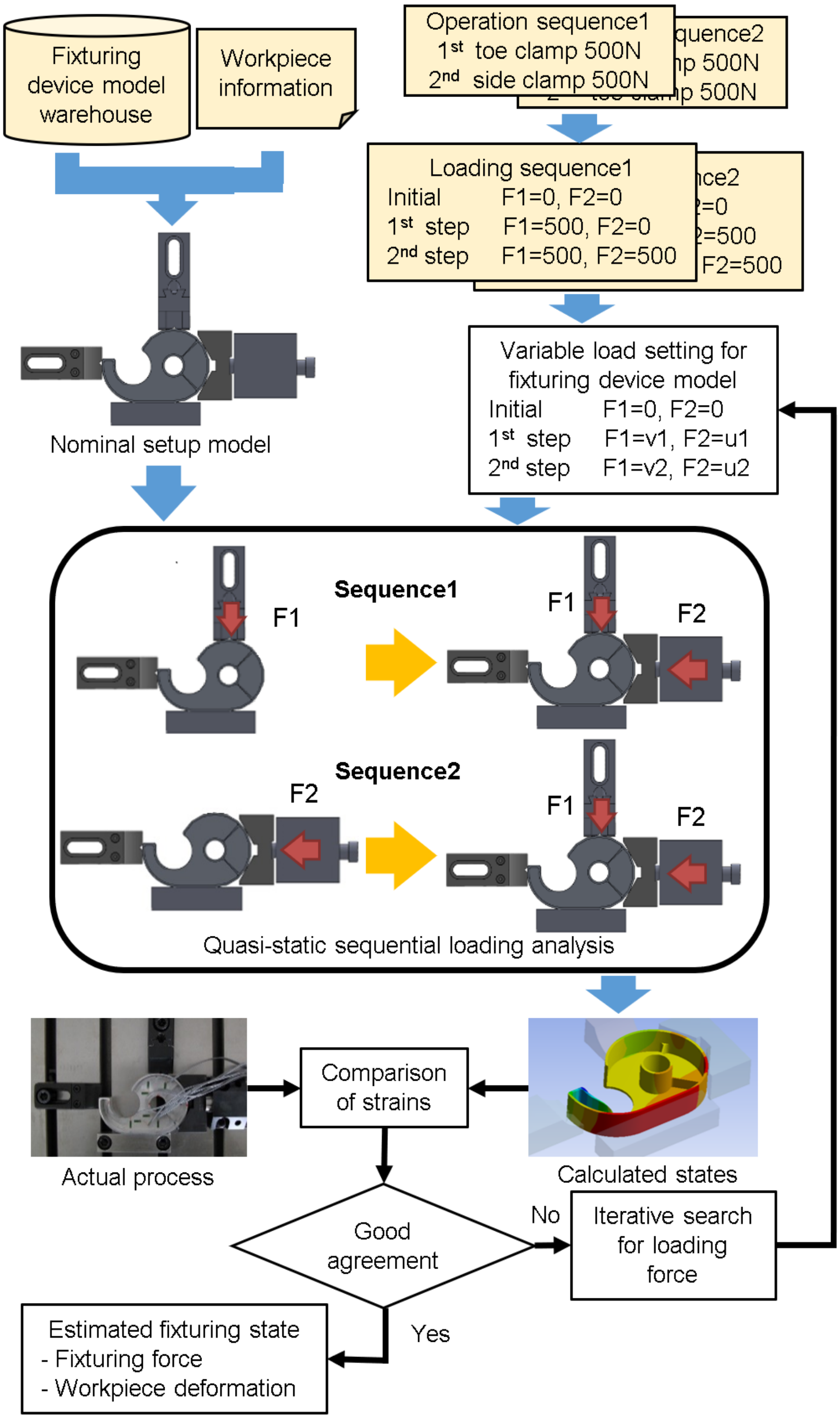


Fig. 4-4 Estimation flow of complex workholding state

step workholding analyses, connectivity to commercial FE 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 [24].

Fig.4-4 represents an estimation flow for complex workholding states such as multi-object and multi-step workholding. In comparison with the case of a simple workholding state as illustrated in Fig.4-2, 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 the actual workholding situation can be obtained. Moreover, representations of loading sequences enable us to consider the variations of different loading sequences.

For the iterative search of appropriate loading forces which generate similar strain distribution to the actual experiment, a general optimization procedure is connected to the multi-object and multi-step FE 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.

4.4 EoP (Effectiveness of measurable points)

Measurement points are the base of this research. So, how to determine the location is also an important topic. In general, the method for determining the location of strain measurement is not clearly defined, and it is mostly determined by experience. Therefore, in this study, we propose a method to determine the location where effective strain measurement can be independently performed. In the research, we focused on two items as conditions for effective measurement. First, the strain must be large to facilitate measurement. Secondly, since it needs to be easily affected by changes in the workholding state, a position where the amount of strain changes greatly when the fixturing force is disturbed is selected. The position that satisfies the above two conditions is the strain measurement position.

1. The strain must be large to facilitate measurement
2. Easy to be affected by fixturing force change.

In this research, increases of fixturing forces caused by torque wrenches and sequence difference of loading forces are considered as dominant process deviation phenomena. Therefore, strain sensitivity to the process parameters such as the value of fixturing forces and clamping sequence is introduced as a second index. Therefore, the effectiveness of measurable points (EoP) is formalized as follows.

$$EOP_i = \frac{\Delta S_{i,n}}{\max_{j\in\{1,N\}}(\Delta S_{j,n})} + \frac{\delta S_i}{\max_{j\in\{1,N\}}(\delta S_j)} \qquad \text{Eq(1)}$$

$$\delta S_i = \max_{k\in\{1,M\}}(\Delta S_{i,k} - \Delta S_{i,n}) \qquad \text{Eq(2)}$$

In Eq. (1), where i represents the nodal number of measurable points (maximum number is N), k represents the number of effective properties set (maximum number is M). $\Delta S_{i,n}$ indicates maximum fixturing force rise of i-th node with nominal boundary conditions setting. δS_j indicates the variance of maximum fixturing force rise against the change of process parameters.

Chapter 5
Case Study

5.1 To confirm the feasibility of On-machine estimation method for thin-walled parts clamping situation

5.1.1 Intention of deformation measurement

The objective of the research is to investigate an on-machine estimation method that can evaluate the deformation of actual thin-wall structured parts. The method is based on a combination of FEM (Finite Element Method) analysis and the local measurement. To utilize the method, the reliability of FEM analysis is important. As the measurement data, we utilize local strain measurements to estimate the deformation of the actual workpiece. Elastic strain is only affected by the local behavior of the workpiece. It means that the strain-based estimate can separate information of the workpiece from the locating error. When the workpiece deformation is within the allowable tolerance range, because the workpiece can be considered as a rigid body, so we just need to evaluate the position and orientation of the workpiece surface which can be measured by a few points.

In this dissertation, workpiece deformation and strains are evaluated. Clamped workpieces with vise fixturing are simulated by using FEM-based elastic analysis. The calculated results are compared with the experimentally measured strain and deformation.

Deformations and strains of a workpiece under the vise fixturing are estimated to evaluate basic functionality.

5.1.2 Actual experiment process

A standard mechanical vise is employed in the experiment. Control values of the mechanical vise are unidirectional fixturing force (F). The fixturing force of the mechanical vise is controlled by tightening torque. A torque wrench is used to add the torque. Relations between the fixturing force and torque of vise are measured in advance. As a fixturing part, a thin-structure workpiece is employed. The shape of the workpiece is illustrated in Fig.5-1. Strain gages glued at evaluation points in Fig.5-2 are employed to measure the strains. The workpiece attached with strain gauges is placed on the mechanical vise, and controlled fixturing force is loaded. Dimensions of workpieces and strain measurement points are illustrated in Fig.5-2. Fig.5-3 illustrates workholding situations and deformation measurement points. Displacements at evaluation points in Fig.5-3 are measured by using dial indicators. As an example of a standard workholding situation, F is controlled as 1000N. The basic process and actual experiment situation are shown in Fig.5-4 and Fig.5-5.

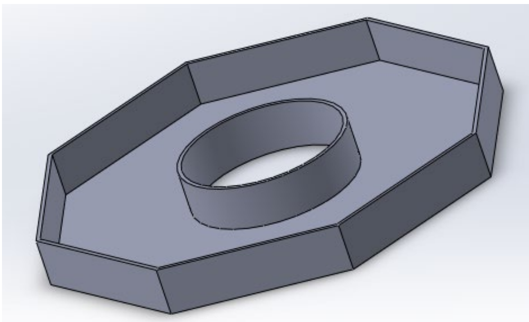


Fig.5-1 Shape of workpiece

Pattern： Faces contact workholding (For general jig)

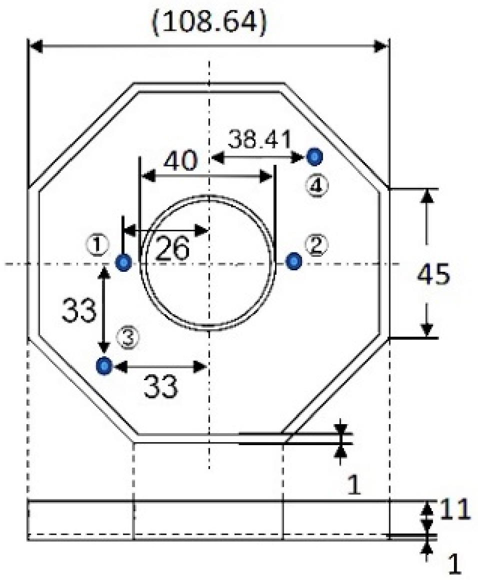


Fig.5-2 Dimensions and strain measurement points

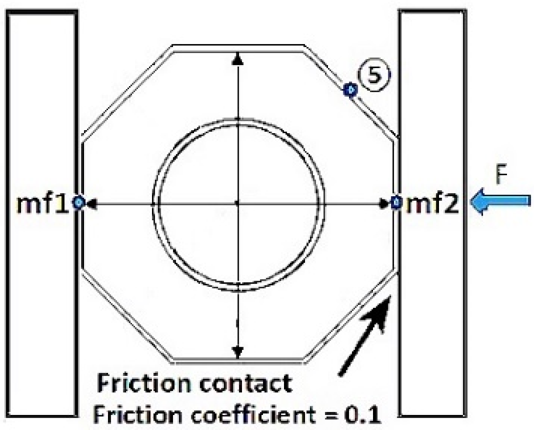


Fig.5-3 Workholding situation and dimensions for evaluation

- ○A standard mechanical vise is employed for fixturing.
- ○Strains are measured at measurement points ① to ④.
- ○The fixturing force is controlled by tightening torque which is calibrated in advance.
- ○The workpiece attached with strain gauges is placed on the mechanical vise.
- ○Deformation is measured at mf1, mf2, and ⑤ by dial gauges.

Fig.5-4 Actual experiment process

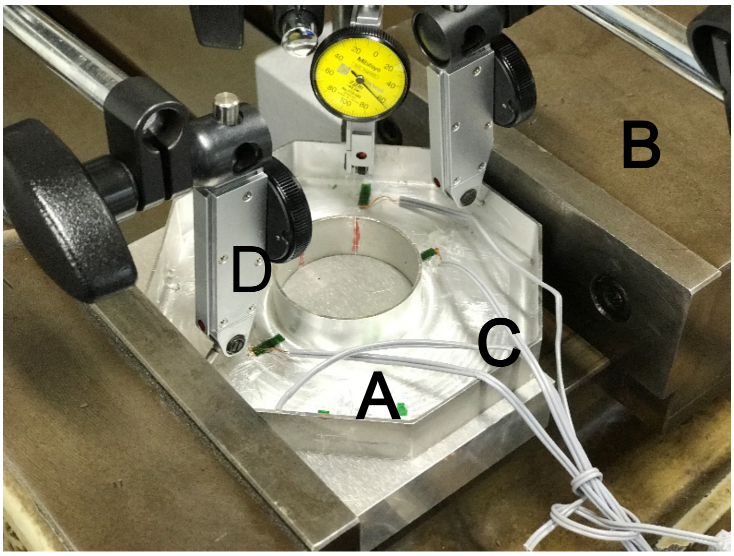


Fig.5-5 actual experiment situation

[A] Measured workpiece

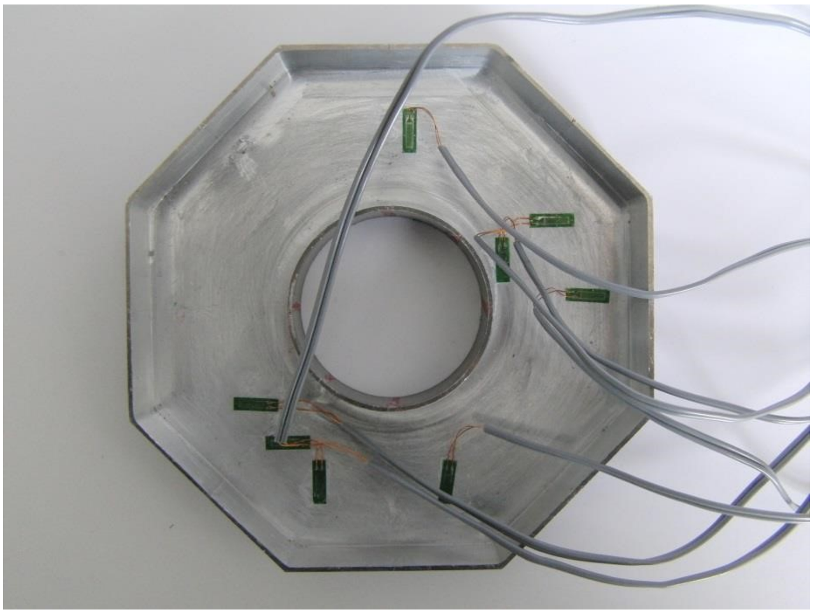


Fig.5-6 Thin-walled octagonal part

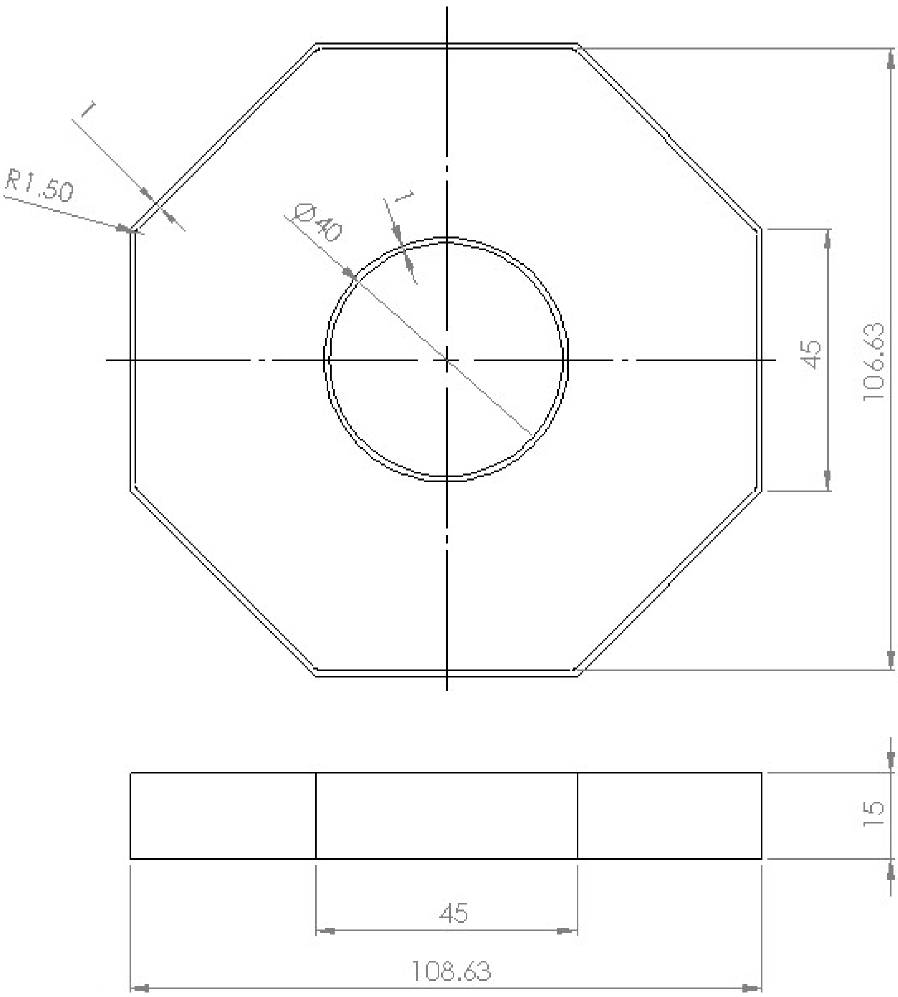
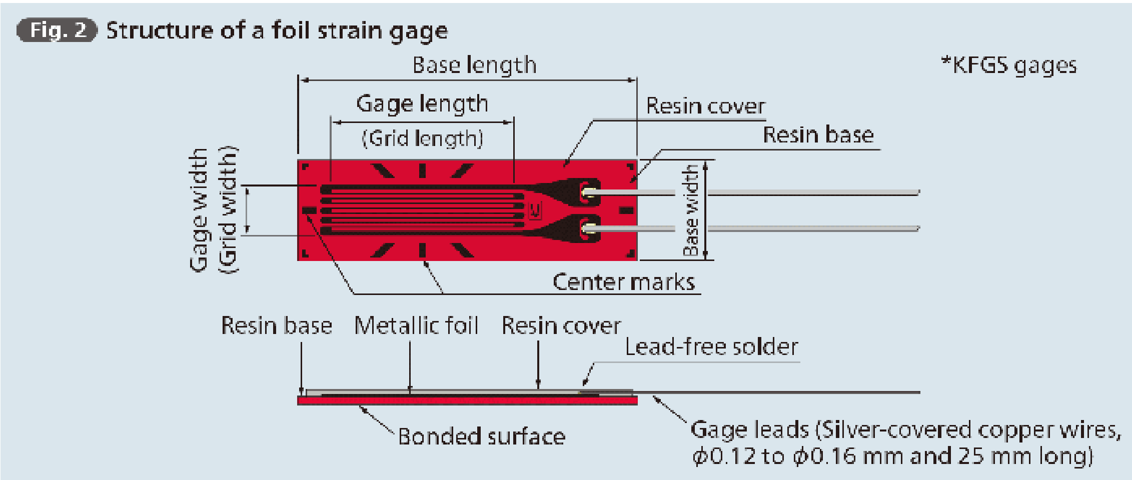


Fig.5-7 Size of thin-walled octagonal part

[B]Standard mechanical vise

Fig.5-8 A standard mechanical vise which used in this time

[C]Strain gauges



The gauge factor GF is defined as:

$$GF = \frac{\Delta R / R_G}{\epsilon}$$

where

ΔR is the change in resistance caused by strain,
R_G is the resistance of the undeformed gauge, and
ϵ is strain.

Fig.5-9 Structure and principle of strain gauge
(https://www.kyowa-ei.com/eng/technical/strain_gages/principles.html)

As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.

[D]Dial gauges

Fig.5-10 Style of dial gauge

Produced by Ltd.Co Mitutoyo

Measurement accuracy　Minimum scale=2μm

[E]Torque wrench

Product by Tohnichi Seisakusho　Type DB50N

Torque range	5 ~ 50 N・m
Minimum scale	0.5 N・m
Torque accuracy	± 3 %

Fig.5-11 Style of torque wrench

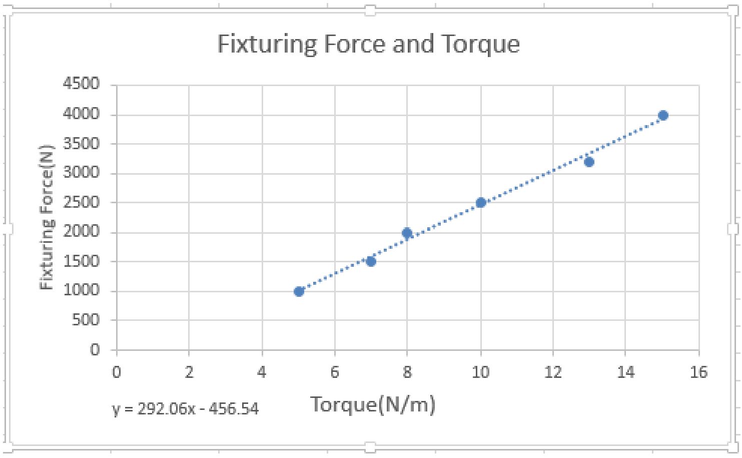


Fig.5-12 Connection between fixturing force and torque

5.1.3 Modeling and solving of workpiece deformation field by FEM

To calculate nominal workpiece deformation, elastic analysis is carried out by using commercial FEM software.

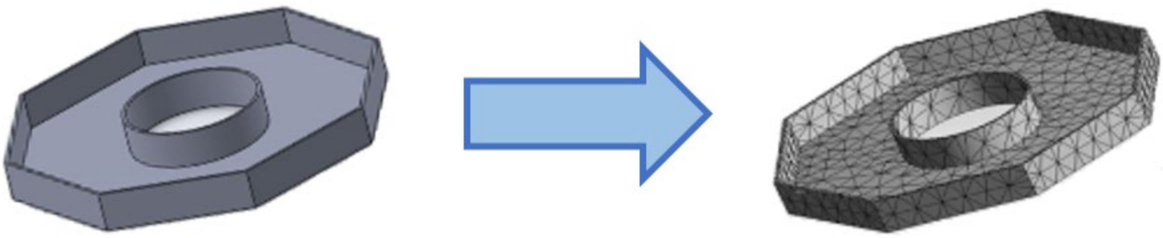


Fig.5-13 Mesh the target workpiece

To calculate workpiece deformation, elastic analysis is carried out by using commercial FEM software (ANSYS Workbench 16.0). For the FEM simulation, the contacts between the workpiece and mechanical vise are modeled as friction contact and the friction coefficient is assumed as 0.1.

○**FEM software: ANSYS Workbench 16.0**

○**Material of workpiece: Aluminum alloy A2017**

○**Fixturing force=1000N**

Fig.5-14 FEM software edition and nominal boundary condition

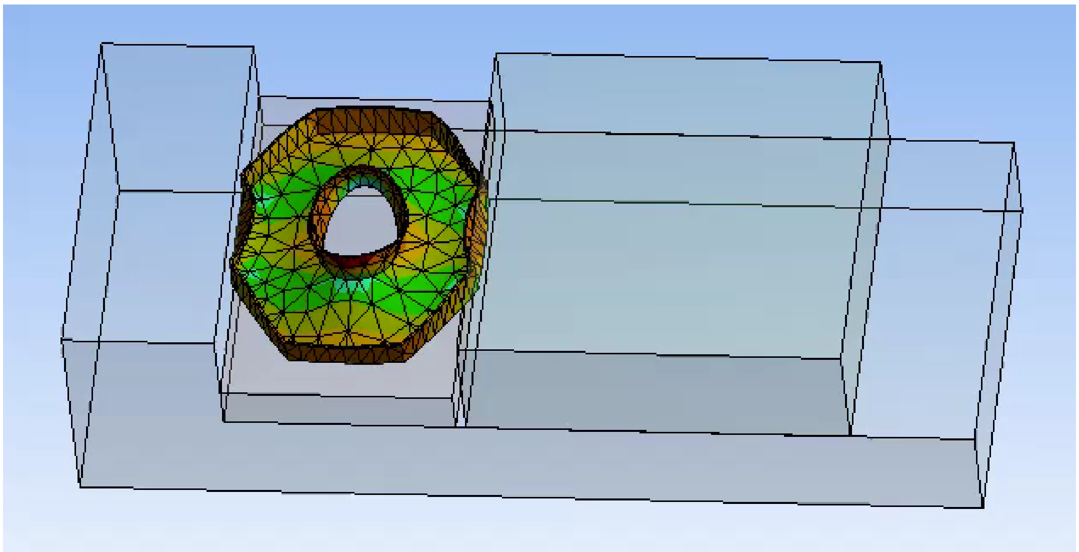


Fig.5-15 Situation of FEM simulation

5.1.4 Results comparison between FEM and Actual experiment

As shown in Fig.5-15, it shows us the gradient of strain distributions is perpendicular to the force direction, the normal strain value close to the edge is bigger than the strain far from the edge. The scene of actual workholding experiment is shown in Fig.5-16. Fig.5-17 and Fig.5-18 illustrate the calculated distribution of nominal strain and workpiece deformation respectively.

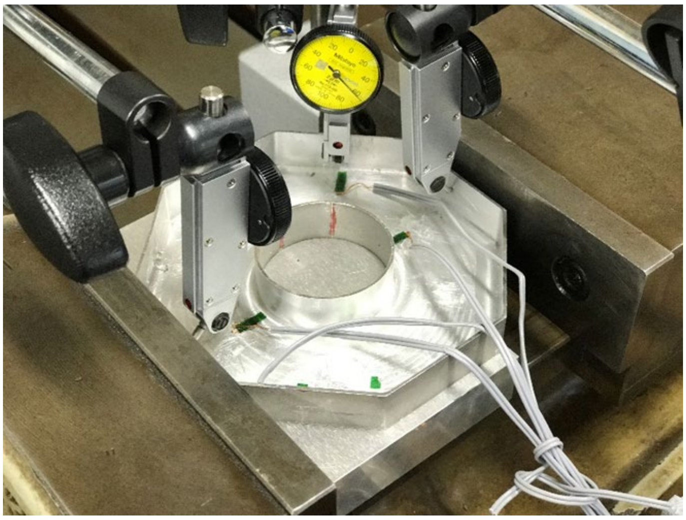


Fig.5-16 Scene of actual experiment

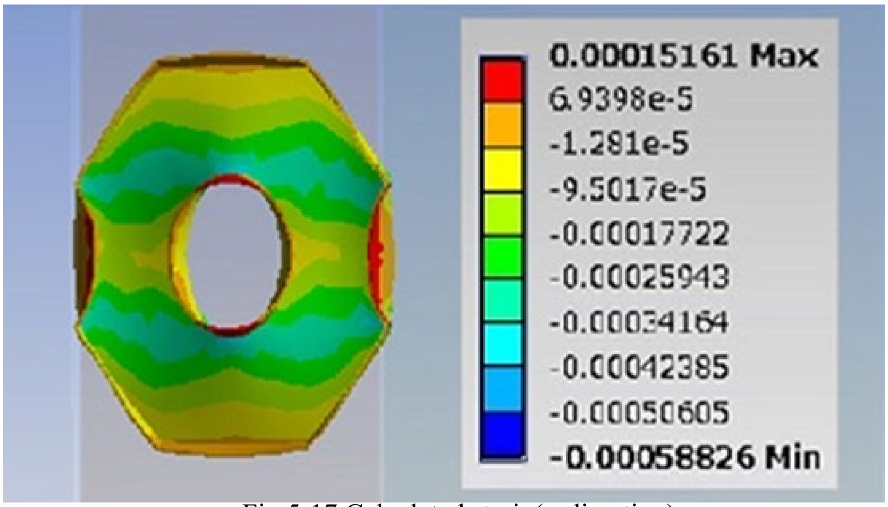


Fig.5-17 Calculated strain(x-direction)

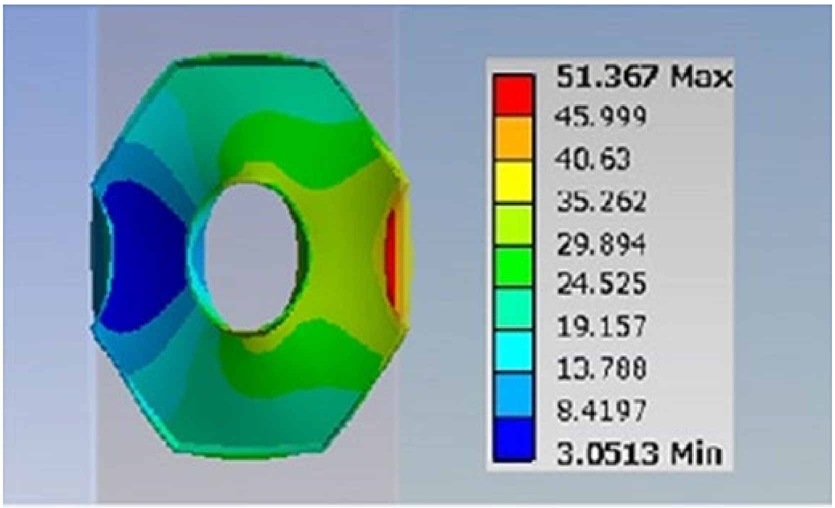
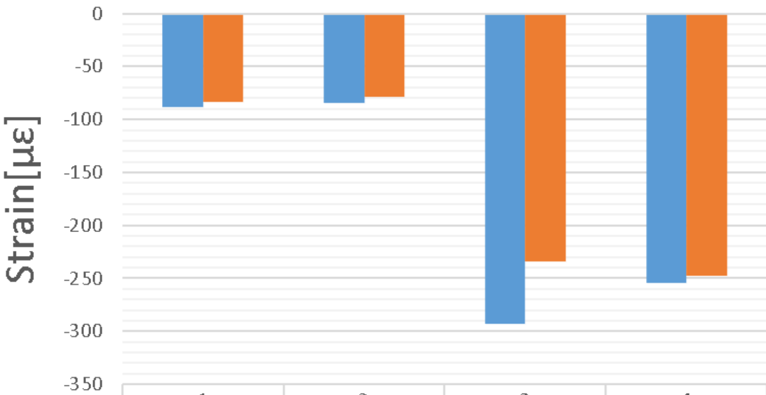


Fig.5-18 Calculated deformation(x-direction)

According to the images of calculated strain and calculated deformation, we can understand the distribution of strain and deformation within the workpiece. The calculated results are compared with measured strain and deformation from the vise fixturing experiment.

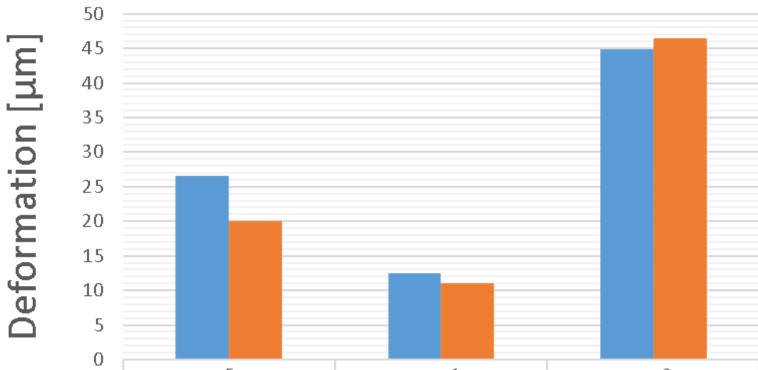
To evaluate calculated results, a workholding experiment with the machined workpiece (material is Aluminum alloy A2017) and a mechanical vise is carried out.

Fig.5-18 and Fig.5-19 show comparisons between calculated results and measured results. Fig.5-17 is comparisons of strain and Fig.5-18 is comparisons of deformation. From the results, the proposed estimation method can estimate the deformation accurately.



	1	2	3	4
FEM	-88.1	-84.2	-293.3	-254.8
Measured	-83.3	-78.4	-234	-247.2

Fig.5-19 Comparison of strains



	5	mp1	mp2
FEM	26.6	12.52	44.9
Measured	20	11	46.5

Fig.5-20 Comparison of deformations

To utilize the hybrid estimation method which combines locally measured strain and FEM-based analysis, the accuracy of FEM-based deformation analysis is evaluated. At the well-controlled workholding situation, the results of FEM analysis show good agreement to the actual fixturing situation. The results of strain and deformation indicate the feasibility of on-machine estimation of thin-structured parts deformation.

5.1.5 Case of multi-points contact workholding

The workholding method of the thin-walled workpiece is an important research topic. When using jigs for workholding, due to the different contact states and the workholding method, we can observe that the deviation happened withholding state in each workholding test. Because the deviation is not only considered to be the displacement of the component, but also considered as the value of the deformation, so it is possible to predict that the component holding state deviates.

There are several reasons for the deviation, so this study conducts actual control experiments for different shapes and workholding methods to verify the impact due to the main cause.

Pattern： Multi-points contact workholding（For complex shape）

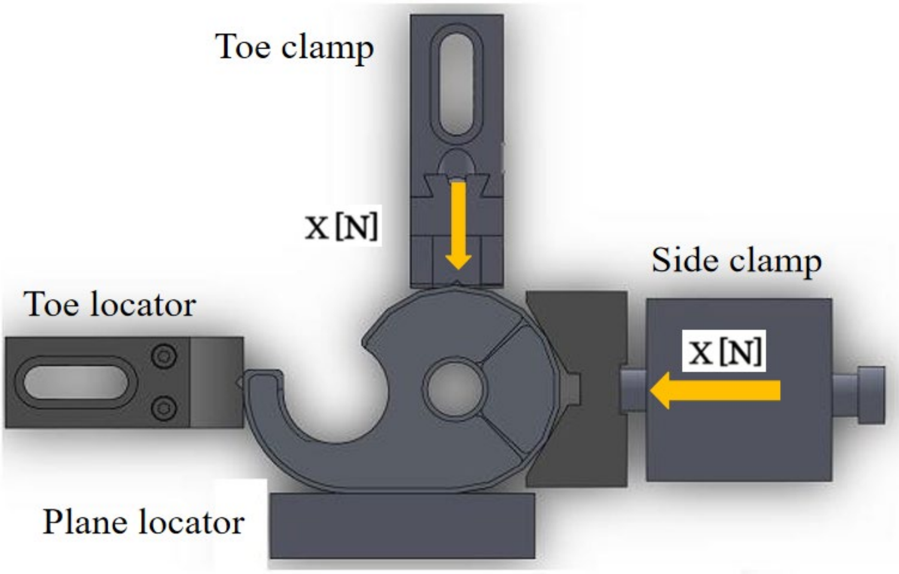


Fig.5-21 Experiment diagram

5.1.6 Actual experiment process

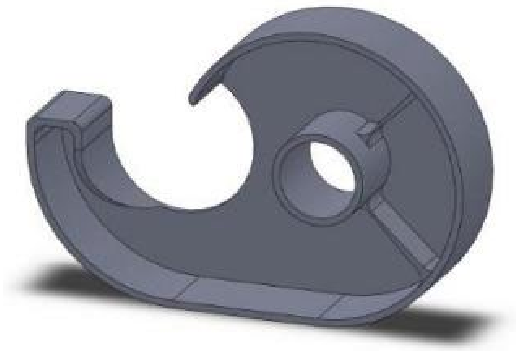


Fig.5-22 Dimensions and strain measurement points

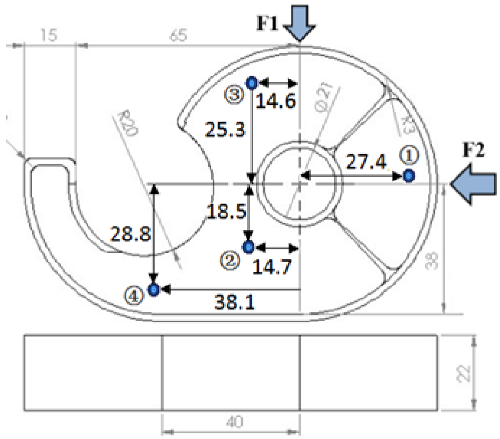


Fig.5-23 Workholding situation and dimensions for evaluation

The shape of parts is illustrated in Fig.5-22. Strain gauges glued at evaluation points in Fig.5-23 were employed to measure the strains in workholding experiment. Because of the limitation of strain measurement equipment, four points of strain were utilized. The locations of strain measurement are determined by considering the magnitude of strain and sensitivity to change in boundary conditions from the workholding simulation. This heuristic determination should be improved more systematically in a practical situation. This is an important future task of this research. The actual workholding experiment scene is shown in Fig.5-24. 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].

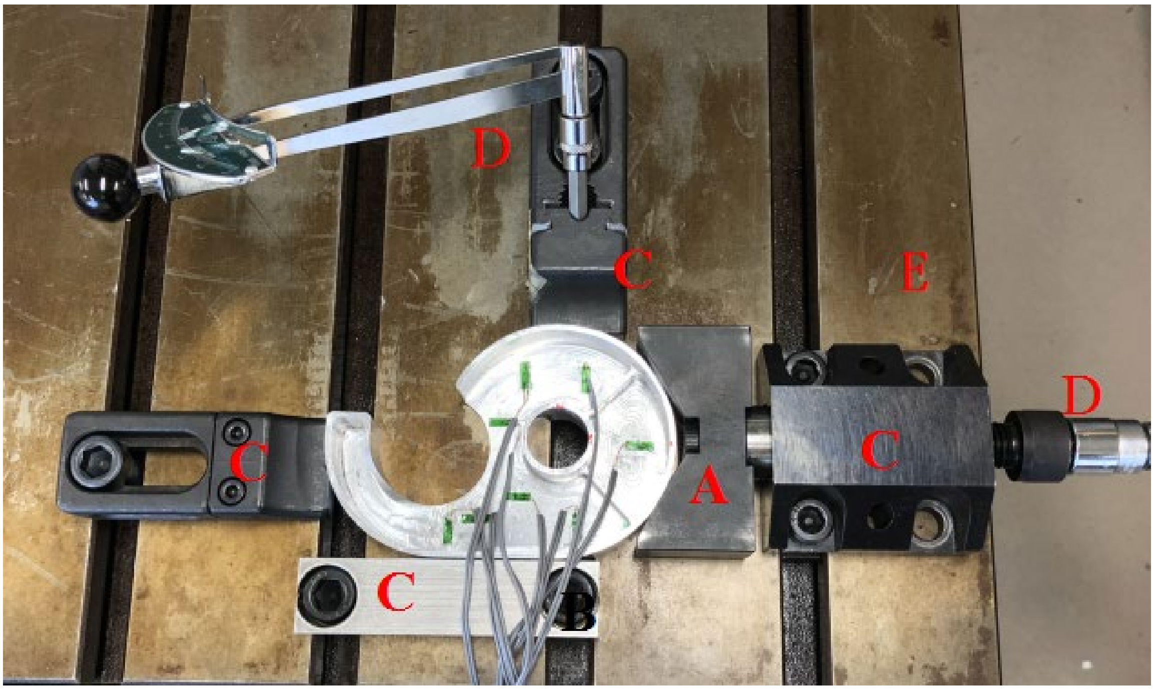


Fig.5-24 Scene of this experiment

[A] Measured workpiece

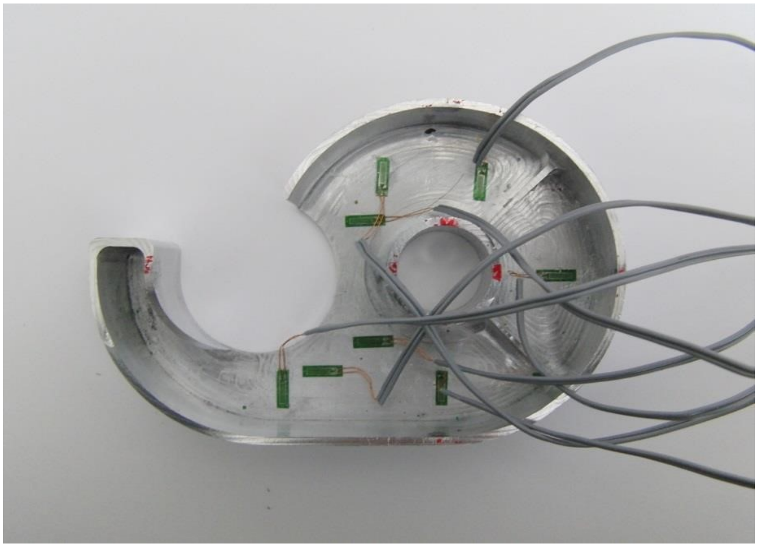
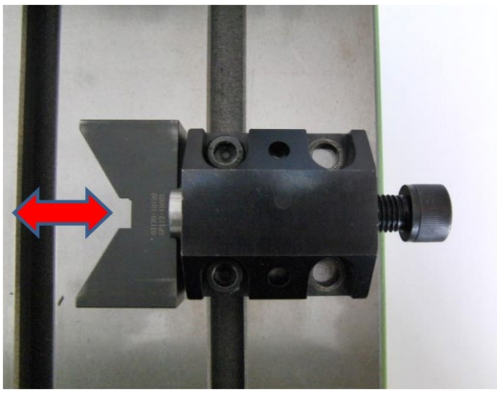


Fig.5-25 Structure of thin-walled part

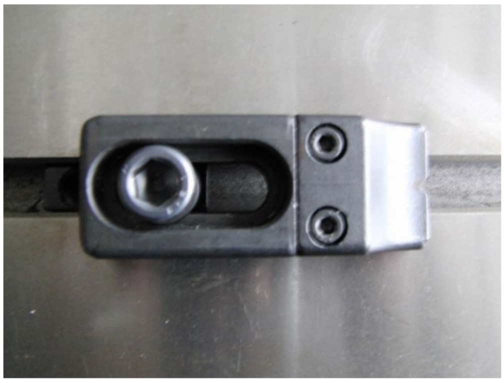
[B] Strain gauges

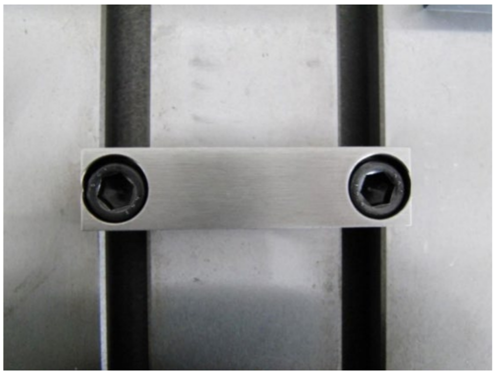
Have already been introduced before

[C] Workholding instruments



Side clamp **Toe clamp**



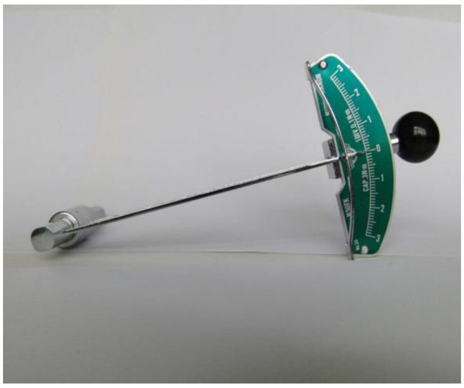


Toe stopper **Plane locator**

Fig.5-26 Photo of workholding instruments

[D] Torque wrench

For grip experiments, the fixturing force must be adjustable. The two clamps used this time control the fixturing force by adjusting the screw torque of the clamp.



Torque wrench SF6N **Torque wrenchN30FK**

Fig.5-27 Photo of torque wrench

Table5-1 . Specifications of torque wrench

Type	Torque measured range[N・m]	Unit scale [N・m]	Length [mm]	Angle drive [mm]
SF6N	0.6～6	0.2	205	6.35
N30FK	1～3	0.1	170	6.35

[E] Load cell

Next, the relationship between the magnitude of the torque and the magnitude of the fixturing force generated was measured. For load measurement, compact compression type load cell was manufactured by Kyowa Electric Industry Co. Ltd. in Fig.5-2 was used. The specifications of this load cell are shown in Table 5-2. Attach the load cell to the tip of the side clamp as shown in Fig. 5-29 and Fig. 5-30. Increase the size of the torque wrench of the side clamp from 1.0 N · m to 6.0 N · m by 0.5 N · m increments, and record the value of the load cell at each value.

Next, the load cell is attached to the tip of the torque lamp, the size of the torque wrench of the torque lamp is increased from 0.2 N · m to 2.0 N · m by 0.2 N · m at a time, record the value of the load cell at each value.

For measurement, repeat load-unloading repeatedly with load cell-attached, repeat loading-unloading measurements 10 times in one measurement set, repeat 5 sets s after removing load cell and reinstalling 50 times in total.

Table 5-3 shows average values of load cells at each torque. A graph is created and the linear relationship between the tightening torque and the fixturing force is obtained.

Table5-2．Specifications of load cell

Type	Rated capacity [kN]	Rated output [μV/V]
LMR-S-2kNSA2	2	1237

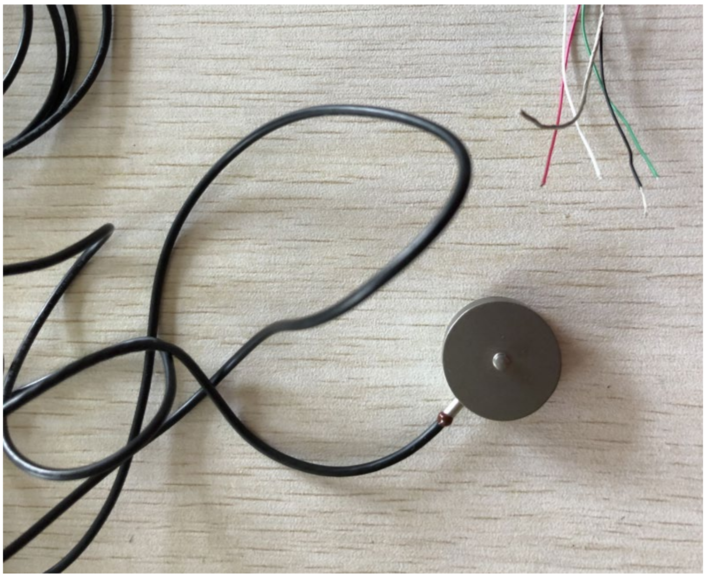


Fig.5-28 Load cell

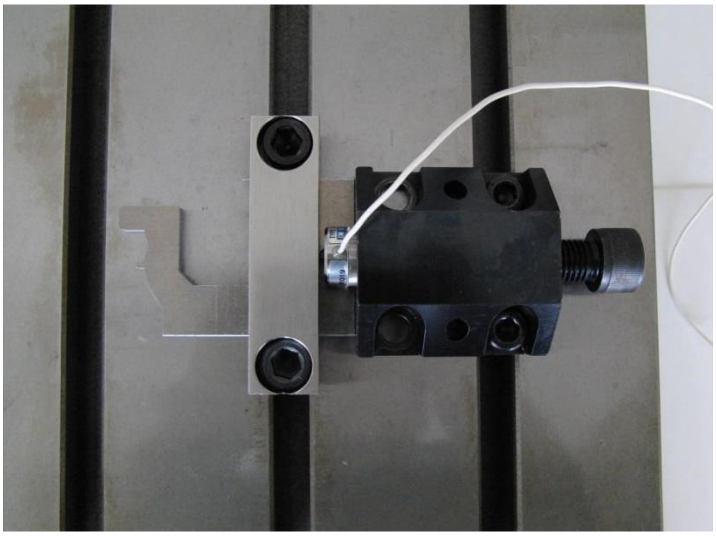


Fig.5-29 Load measurement of side clamp and topside

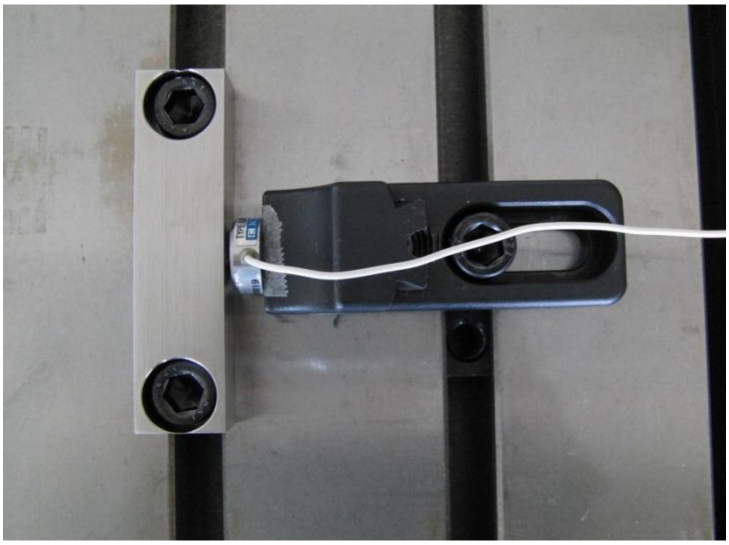


Fig.5-30 Load measurement of side clamp and topside

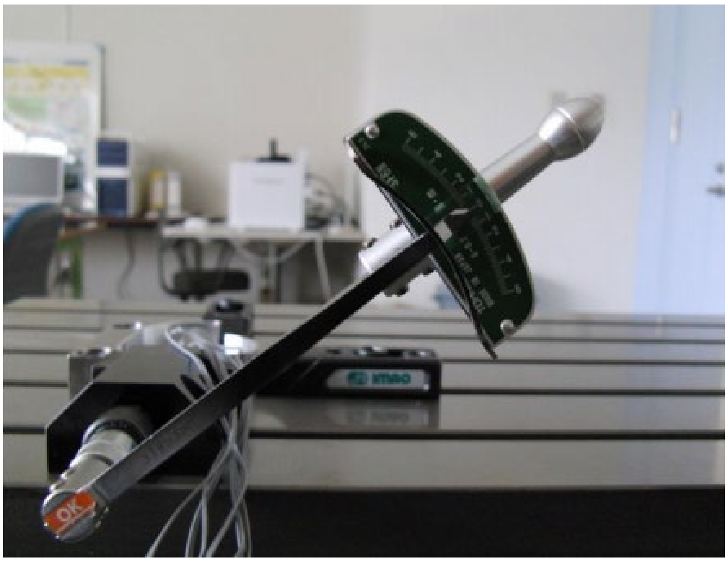


Fig.5-31 Situation of torque wrench SF6N used

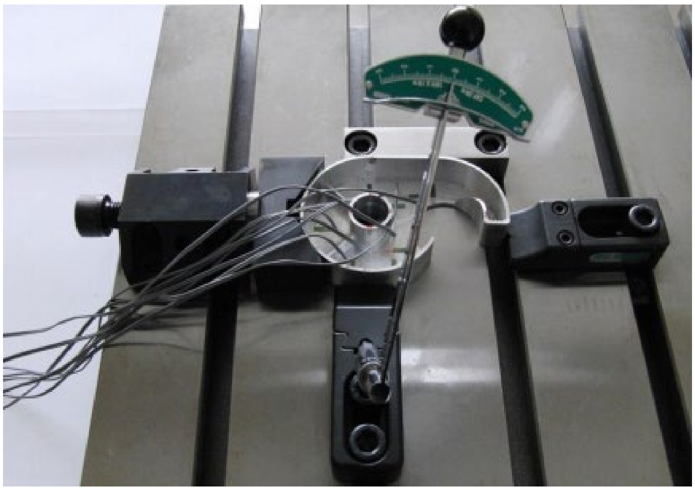


Fig.5-32 Situation of torque wrench N30FK used

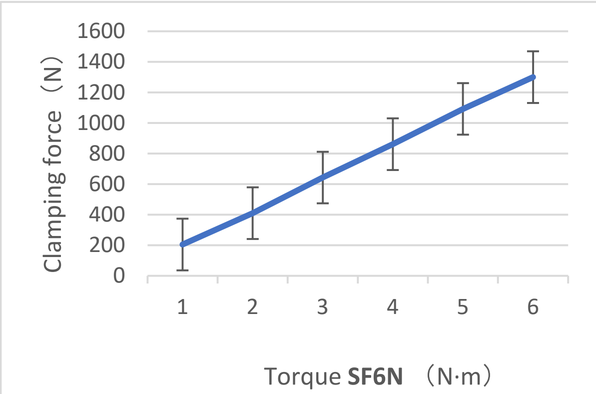
Table5-3．Relationship between torque and fixturing force

Torque	Force
N・m	N
1	205
2	410
3	643
4	861
5	1092
6	1300

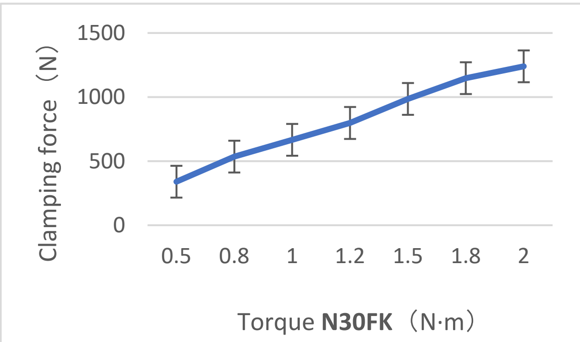
Torque SF6N

Torque	Force
N・m	N
0.5	340
0.8	535
1	666
1.2	798
1.5	985
1.8	1148
2	1240

Torque N30FK



Torque	Force
N・m	N
2.4	500
2.8	600
3.3	700
3.7	800
4.2	900
4.6	1000
5.1	1100



Torque	Force
N・m	N
0.7	500
0.9	600
1.05	700
1.2	800
1.4	900
1.55	1000
1.7	1100

[F]Digital micrometer

In this experiment, digital micrometer was used to measure the deformation of workpiece.

Type	Measurement range [mm]	Minimum display [mm]
IMP-50MB	25～30	0.001

Fig.5-33 Situation of torque wrench N30FK use

5.1.7 FEM simulation process

To calculate workpiece deformation, elastic analysis is carried out by using commercial FEM software (ANSYS Workbench 16.0). The material of workpiece is aluminum alloy A2017. Fig.5-34 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.5-35. To simulate this workholding process, boundary conditions are set as listed in

Table 5-4. Contact parts materials of workholding instruments are steel and stainless 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 steel vary from 0.45 to 0.02 depending on the roughness, lubrication, and literature [60-63]. 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 was set as 0.1.

Table. 5-4 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
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)

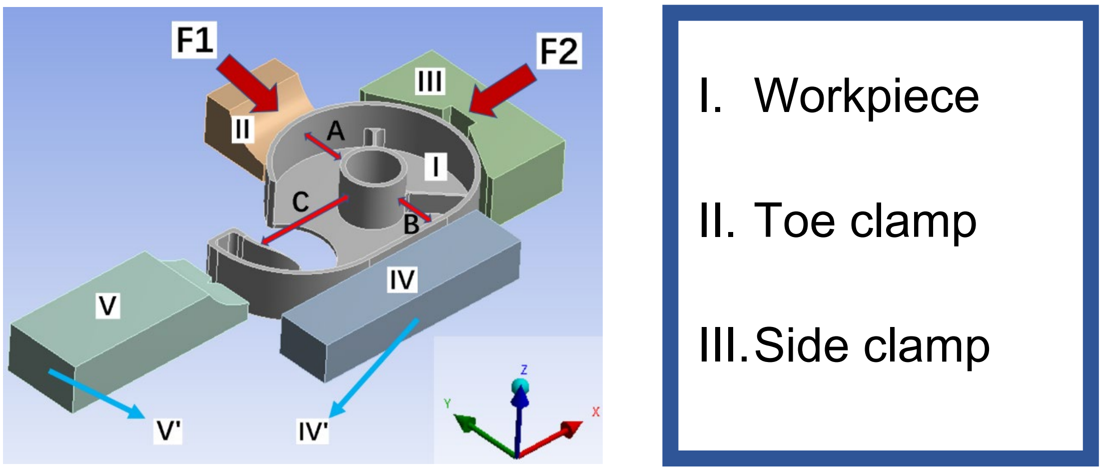


Fig.5-34 FEM simulation situation

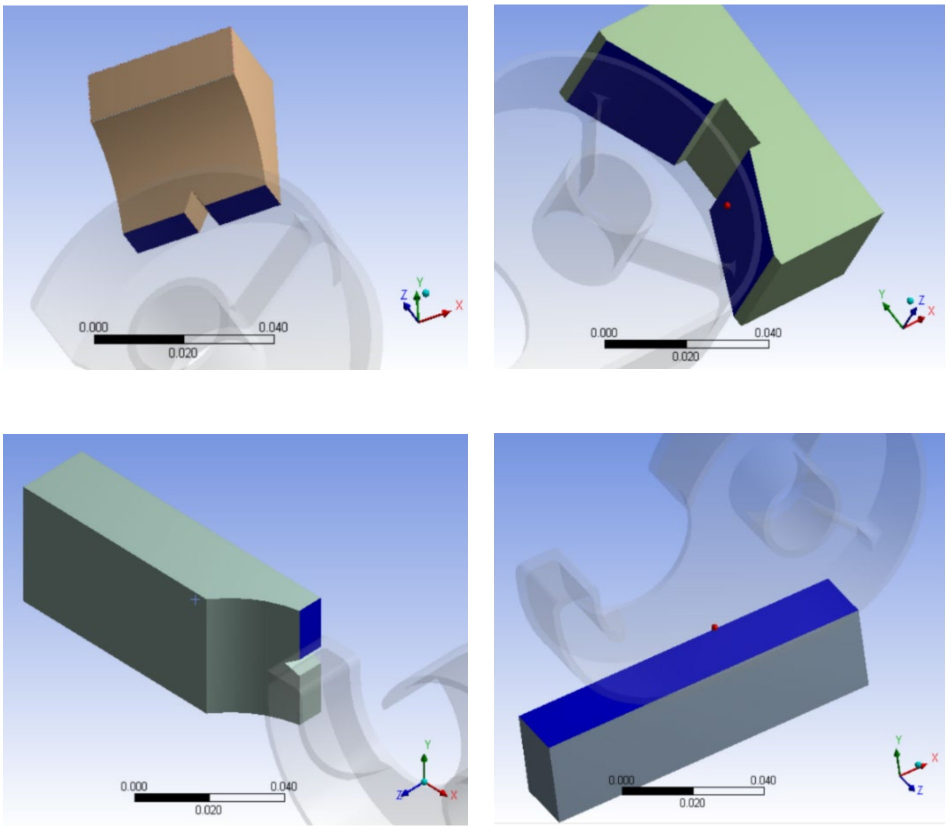


Fig.5-35 Contact surfaces of workpiece and workholding instruments

5.1.8 Results comparison

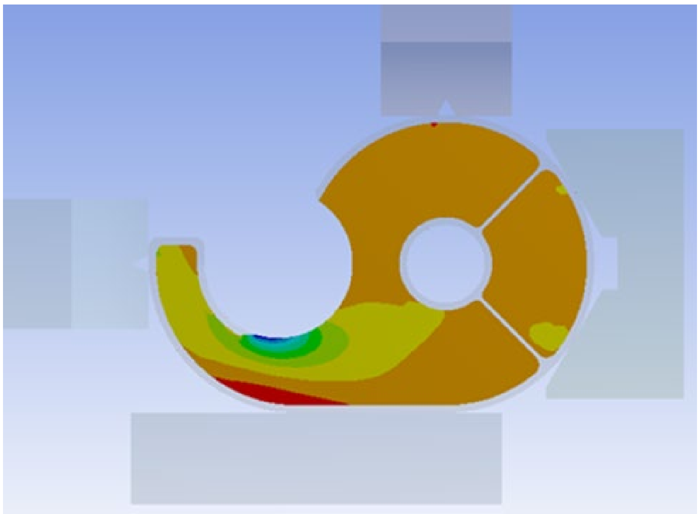


Fig.5-36 Strain distribution

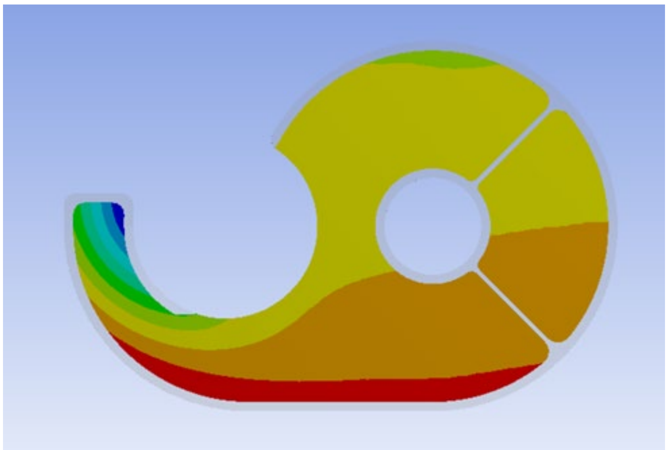


Fig.5-37 Deformation distribution

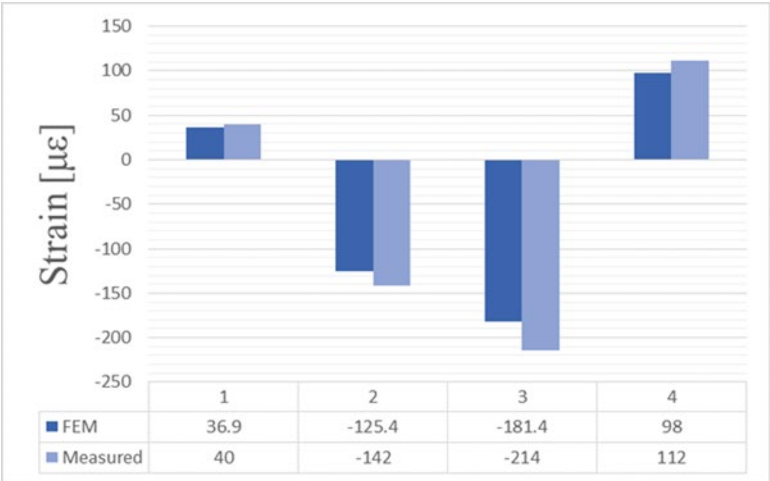


Fig. 5-38 Comparison of strains ① to ④

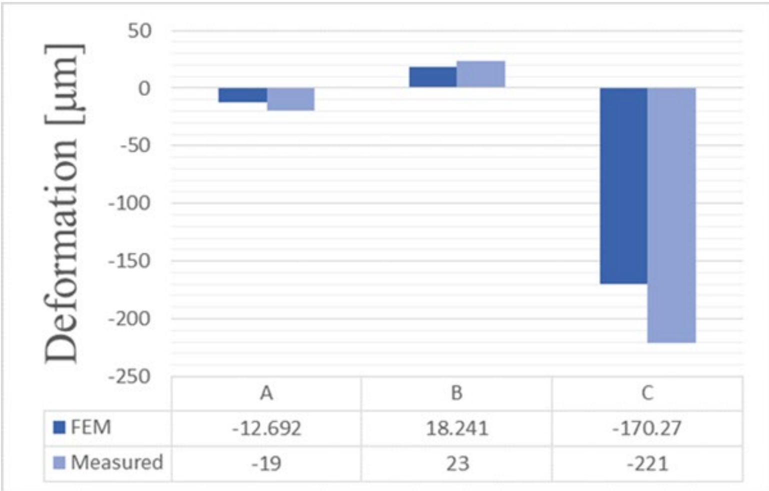


Fig. 5-39 Comparison of deformations A to C

We could see the calculated Strain distributions and Deformation distributions in Fig.5-36and Fig.5-37. Through the comparison between FEM simulation and actual workholding experiment, we got the results in Fig.5-38 and Fig.5-39. From the result comparison, analyzed deformations are smaller than the measured deformations, results show enough good agreement to the actual fixturing situation in large deformation.

5.1.9 Summary

The results of deformation by FEM analysis show similarity to the actual fixturing situation in large deformation. Analyzed deformations are smaller than the measured deformations.

To utilize the hybrid estimation method which combines locally measured strain and FEM-based analysis, the accuracy of FEM-based deformation analysis is evaluated. At the well-controlled fixturing situation, the results of FEM analysis show good agreement to the actual fixturing situation. The results of strain and deformation indicate the feasibility of on-machine estimation of thin-structured parts deformation.

5.2 Response surface estimation

5.2.1 Pricinple illustration

A description of response surface methodology (RSM) covers how it is used and some of its applications in product optimization. This methodology has evolved into a useful statistical system within the production evaluation field. RSM uses quantitative data from appropriate experimental designs to determine and simultaneously solve multivariate equations that can be graphically represented as response surfaces. These surfaces describe how the test variables affect the response, provide information on the interrelationships among the test variables, and describe the combined effect of all test variables on the response. Fig.5-40 representations of the flow of RSM are illustrated (In this research, we are working on the responses of measured points strain between fixturing force in workholding process). This information aids product developers to understand ingredient interactions in the product which guide final product formulation and future cost and quality changes.

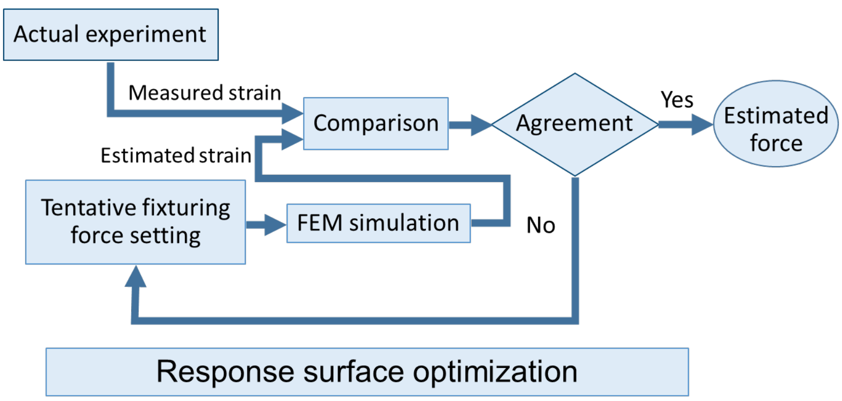


Fig.5-40 Flow of Response surface Method (RSM)

5.2.2 Case of different workholding situation

Workholding process situation by FEM was shown in Fig.5-41. The direction of F1 is X-axis negative direction, the direction of F2 is Y-axis negative direction. To confirm the feasibility and reliability of the response surface method (RSM) which is used in workholding process optimization, we set up three cases for comparison and reference, concrete settings as follows:

Table. 5-5 Fixturing force setting

	Fixturing force[N]	
Settings	F1	F2
Setting 1	200	500
Setting 2	500	200
Setting 3	500	500

Table. 5-6 Optimization setting

Response surface Type	Standard Response surface-Full 2nd Order Polynomials (Widely used in statics and thermal).

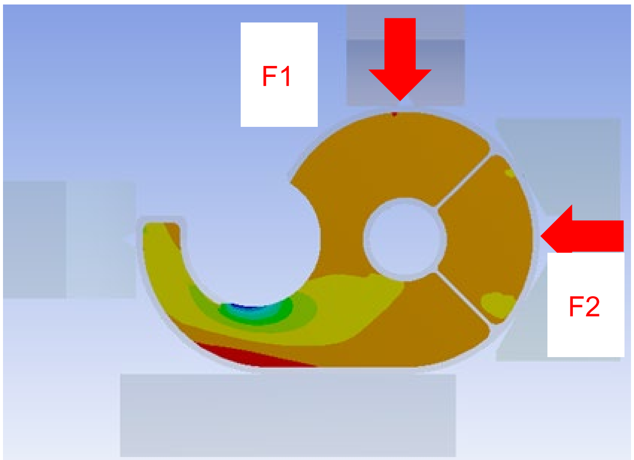


Fig.5-41 Workholding process situation by FEM

5.2.3 Optimization settings of fixturing forces by RSM

This optimization is based on the research of feasibility verification of the On-machine estimation method (Chapter4 section1 Multi-points contact workholding), the measured points are also the same as that case. To reduce the effect of unavoidable error (Such as manual operation or shape and location error), the range of fixturing force was set as 1 to 1000N which was shown in Fig.5-42.

Value	500
Lower Bound	1
Upper Bound	1000
Value	200
Lower Bound	1
Upper Bound	1000

Fig.5-42 Range's setting of fixturing force

About optimization settings, we select Response surface Type as Standard Response surface-Full 2nd Order Polynomials (Widely used in statics and thermal). The calculated minimum and maximum result of strain value by FEM were used as the lower and upper bound.

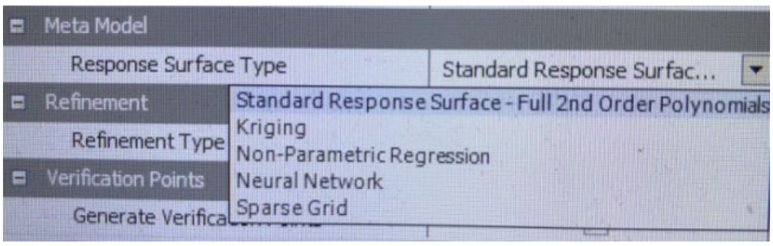


Fig.5-43 Response surface typesetting

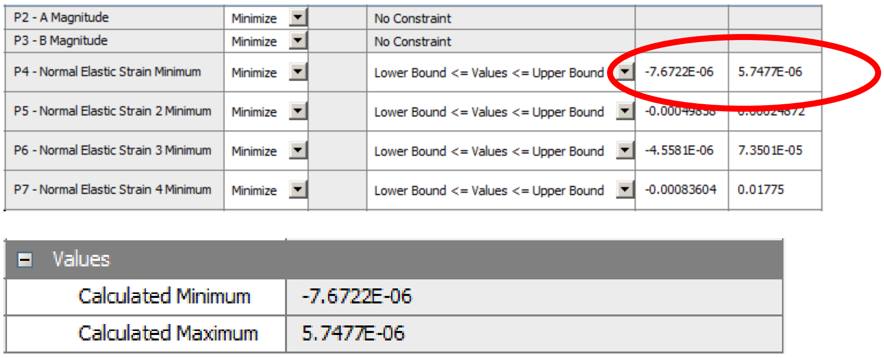


Fig.5-44 Range of normal strain

5.2.4 Results of workpiece deformation estimation

The estimated results are shown in Table.5-7. Figure 5-45 illustrates a comparison between nominal and estimated forces. The error rates of force estimation are smaller than 20%.

Table. 5-7 Result of estimated fixturing force

Setting	Estimated fixturing force
F1=200N F2=500N	F1=176.32N F2=545.6N
F1=500N F2=200N	F1=563.44N F2=168.16N
F1=500N F2=500N	F1=400.2N F2=594.66N

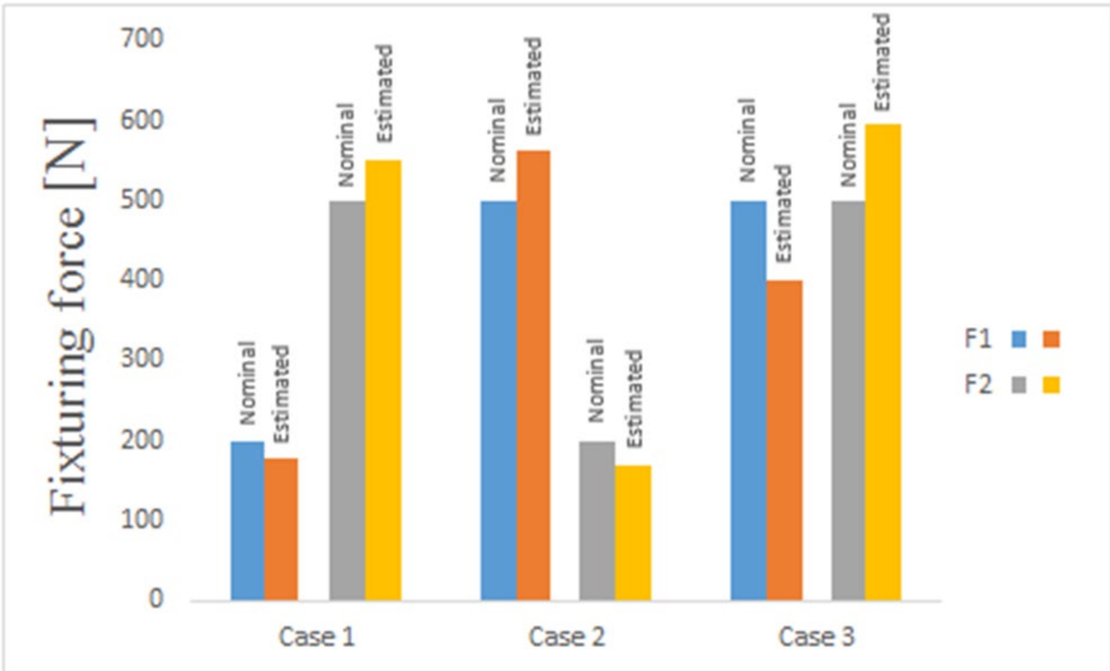
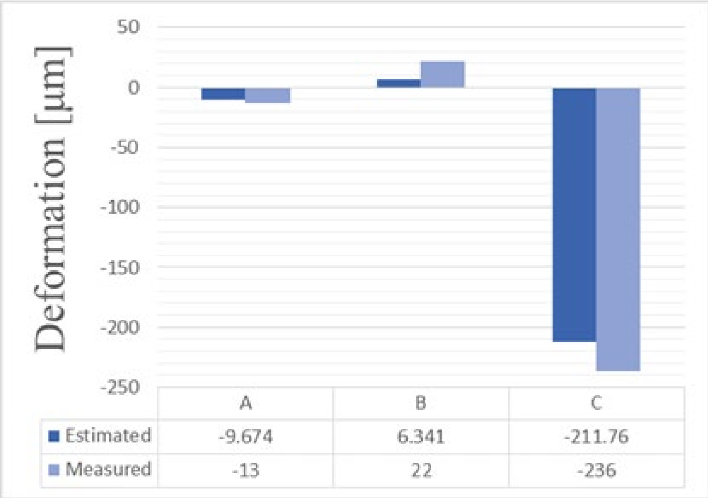


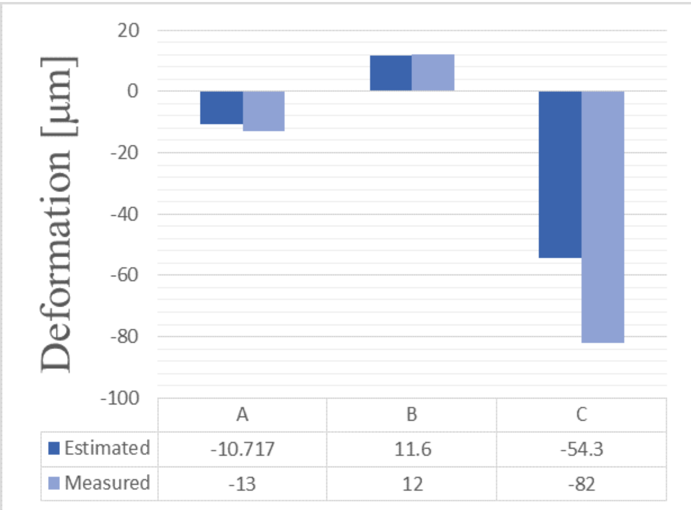
Fig.5-45 Comparison of Nominal/Estimated fixturing forces



Difference rate

A	B	C
25%	71.3%	10.2%

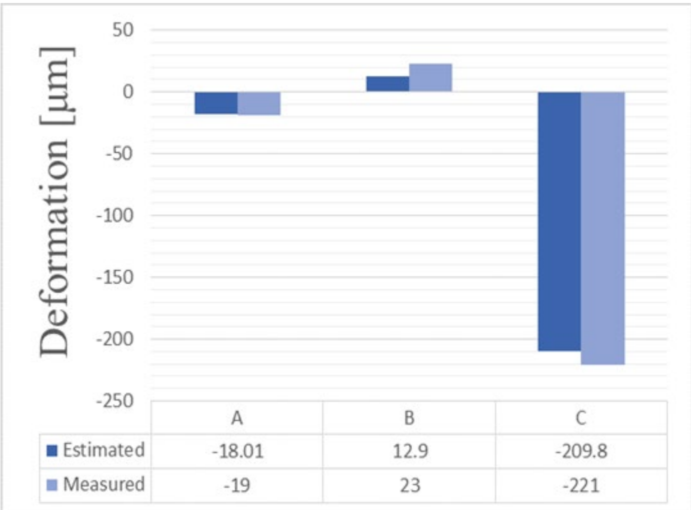
(a) Comparison of Case 1



Difference rate

A	B	C
17.6%	3.3%	34.1%

(b) Comparison of Case 2



Difference rate

A	B	C
5.5%	43.4%	5%

(c) Comparison of Case 3

Fig.5-46 Comparison of deformations (Estimated and Measured)

To evaluate the estimated deformation, corresponding workpiece deformation (dimension A to C in Fig.5-35) of estimated fixturing forces of Case1-3 are obtained. Comparisons of estimated deformation and measured deformation are shown in Fig.5-46. From these results, the estimated deformations with response surface optimization are smaller than the measured deformations and the average difference is about 22%. This indicates the proposed method can estimate accurate deformation results and estimated thin-walled parts deformation.

5.2.5 Summary

To achieve an on-machine estimation of workholding situation, evaluation of FEM analysis and fixturing force estimation are carried out. FEM analysis can represent complicated shape workpieces for complex workholding situations. As a feasibility study of the proposed method, evaluations of the strain and deformation are experimentally investigated. The results indicate the proposed method can estimate the fixturing force and workpiece deformation of the thin-walled workpiece.

5.3 Effect of clamping sequence

5.3.1 Intention of research on different clamping sequence

Fixture geometric error and elastic deformation of the fixture and part are always due to clamping forces, the clamping sequence used can also influence pat position and orientation. Considering the friction between the workpiece and the clamp element, the mechanical model of the relationship between the size of the multiple clamping force, the point of action, and the clamping sequence is established. The influence of multiple clamping forces and contact forces on the deformation of the workpiece is quantitatively analyzed. On this basic concept, the mathematical modeling of the preferred clamping force, the action point, and the clamping sequence is developed. Taking the typical clamping scheme as an example, the influence process of multiple clamping forces and clamping sequence on the deformation of the workpiece is analyzed. The results show the method can analyze the rationality of multiple clamping forces, action point, and clamping sequence.

5.3.2 Experiment and simulation of example workholding problem

Workholding method and measured dimensions (A-E) for deformation evaluation are similar with Fig.5-21, other two measured dimensions(D-E) were added to better know the overall deformation, it's shown in Fig.5-47. 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).

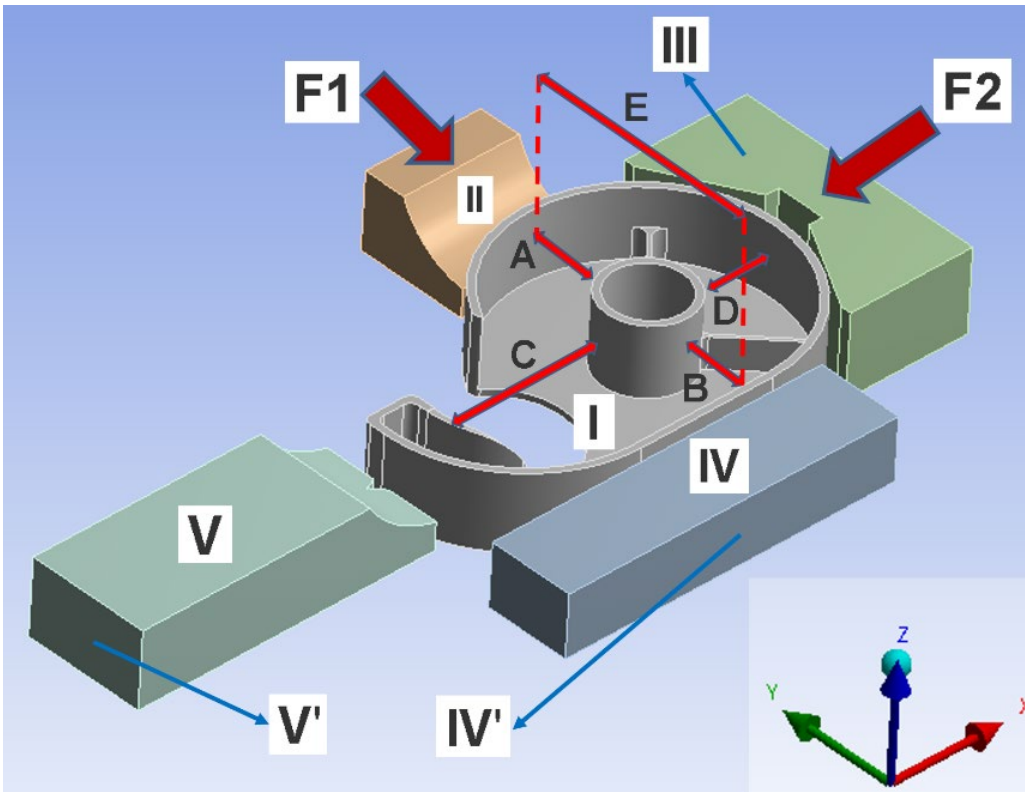


Fig.5-47 Workholding setup and deformation measured position

Contact surfaces of workpiece and workholding instruments are the same as Chapter.5.2 and are shown in Fig.5-36. To simulate this workholding process, boundary conditions are set as listed in Table 5-4. The fixturing force and sequence setting are shown in Table 5-8 and Table 5-9. Contact parts materials of workholding instruments are steel and stainless 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 steel vary from 0.45 to 0.02 depending on the roughness, lubrication, and literature [26-29].

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 was set as 0.1.

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 [64].

For load measurement in the preliminary experiment, an 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, repeat loading-unloading measurements 10 times in one measurement set, repeat 5 sets after removing load cell, and reinstalling 50 times in total.

Table. 5-8 Fixture force/sequence 1 setting

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

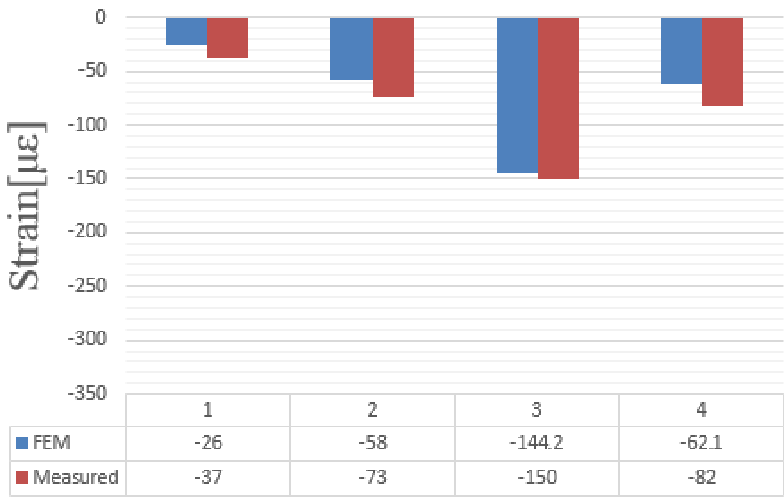
Table. 5-9 Fixture force/sequence 2 setting

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

To simulate the sequential workholding process, quasi-static sequential boundary conditions were set as listed in Table5-1 and Table5-2. For example, the load is set to F1=500N as the first fixturing force and F2=200N as the second fixturing force as Sequence 1 in Table 5-8. By assuming the whole process is 2 steps, the fixturing forces at the initial step are F1 = F2 = 0 N.

The fixturing forces at the first step are set as F1 = 500 N, F2 = 0 N. Next, the fixturing forces at the second step are set as F1 = 500 N, F2 = 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 F1 = 500 N, F2 = 1 N for Sequence 1 and F1 = 1 N, F2 = 200 N for Sequence 2 respectively.

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 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.5-48. The results of the deformation comparison are shown in Fig.5-49. Deformations were measured by digital micrometers and measured values were average values for 15 measurements.



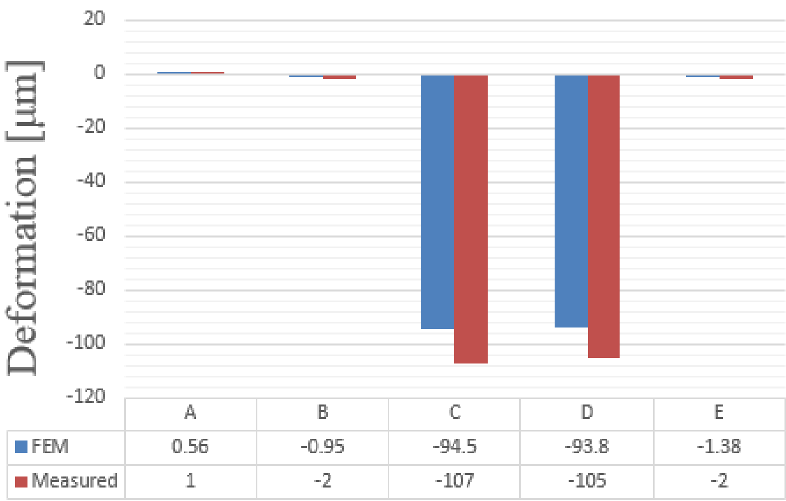
(a) Comparison of strains ① to ④ for Sequence 1

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

Fig.5-48 Comparison of strains (FEM and measured)

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

Fig.5-49 Comparison of deformations (FEM and measured)



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

Fig.5-49 Comparison of deformations (FEM and measured)(Cont.)

Although analyzed strains and deformations show reasonable agreement (the 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 the 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 F1 as the first fixturing force is better than F2. Therefore, confirming the clamping sequence in an actual workholding situation is important to achieve precision machining of thin-walled parts.

5.3.3 Estimated results of workholding states

The assumed workholding process situation is the same as Section 3 illustrated in Fig.5-47. F1 and F2 indicate fixturing forces applied by the 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.5-47 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 5-5 and Table 5-6. In these cases, we assume the 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 F1 and F2 were set for each machining sequence. From the measured strains and FE 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 [65-67]. The mathematical optimization model which was introduced in Chapter5.3 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 1000N. 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.5-50. The average deviation rates of force estimation for all estimations are smaller than 10%.

To evaluate the estimated deformation, corresponding workpiece deformations (dimensions A to E in Fig.5-47) calculated from estimated fixturing forces of Sequence1 and 2 are obtained. Comparisons of estimated deformation and measured deformation are shown in Fig.5-51. The estimated results show a similar tendency to the simulation results (Fig. 5-49). 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 can detect the difference of different workholding situations from the measured strains.

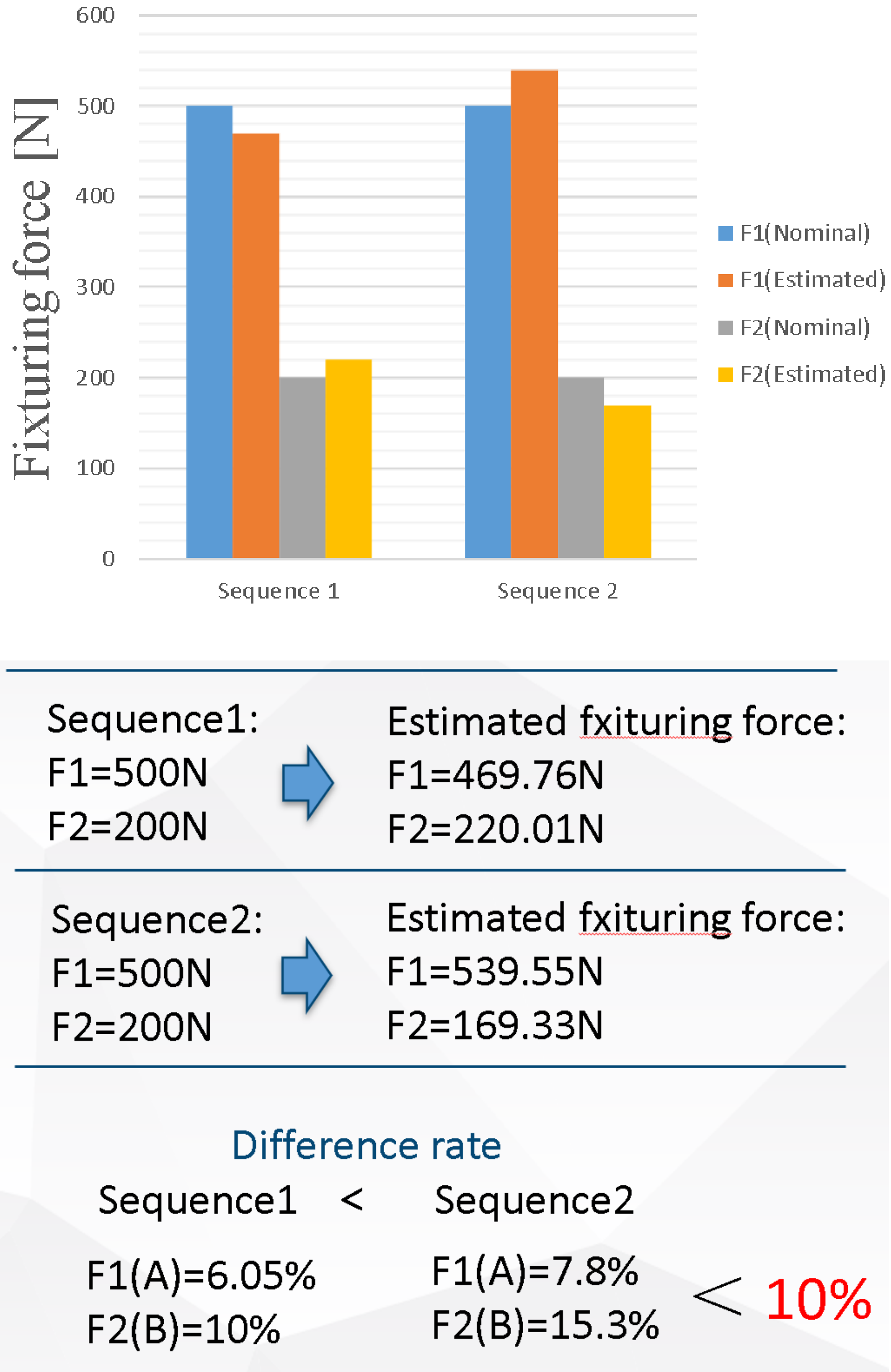
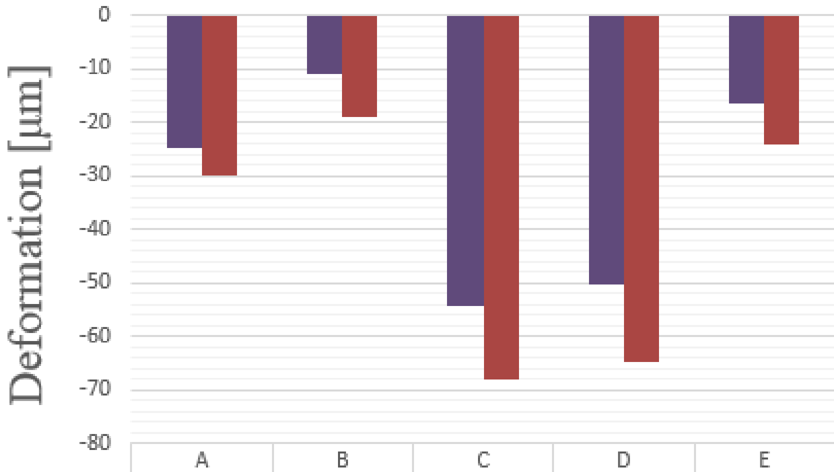


Fig.5-50 Estimated result of fixturing forces



	A	B	C	D	E
Estimated	-24.7	-11.1	-54.4	-50.5	-16.6
Measured	-30	-19	-68	-65	-24

(a) Comparison of Sequence 1

	A	B	C	D	E
Estimated	0.58	-0.63	-86	-86.5	-1.38
Measured	1	-2	-107	-105	-2

(b) Comparison of Sequence 2

Fig.5-51 Comparison of deformations (estimated and measured

5.3.4 Summary

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.

5.4 Measurement points determination

5.4.1 Process describe of measurement points determination

A systematic method to determine the measurement points is also an important research topic to be solved. About this research, we proposed a method for acquiring strain measurement points based on a finite element calculation model, including:

1. Finite element modeling obtains a 2D surface layer of divided units;

2. Calculate the strain values of all elements in the 2D surface layer under each independent external force input load;

3. Select several finite element elements on the 2D surface layer as candidate elements;

4.; Select n candidate units as candidate measurement points from the candidate units, and calculate n candidate measurement points according to the strain value of each candidate measurement point under the action of each independent external force input load corresponding strain-load relationship matrix;

5. Select n candidate measurement points corresponding to the strain-load relationship matrix that are not only stable to changes under the initial boundary conditions (EoP1) but also sensitive to changes in the target boundary conditions (EoP2), as the multi-load strain measurement points, the main concept can be expressed as EoP algorithm in Fig.5-52.

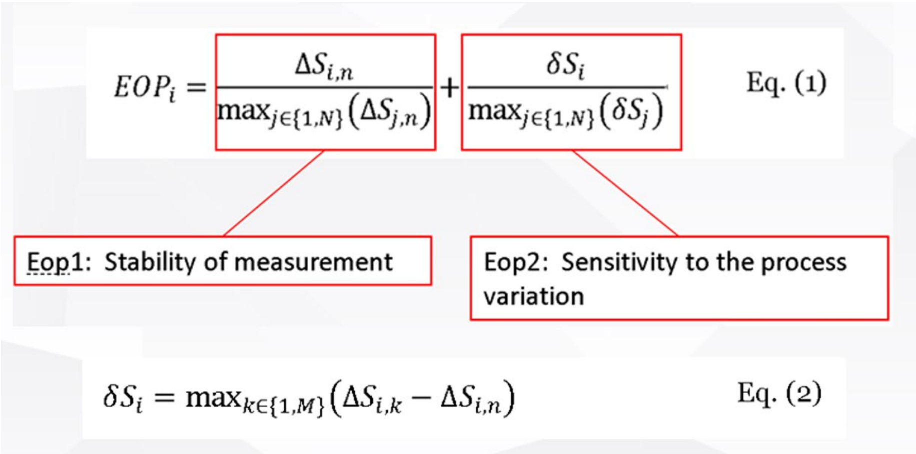


Fig.5-52 Explanation about EoP algorithm

5.4.2 Tooling the EoP algorithm

Even we understand the algorithm of measurement points determination, but how to deal with the huge data and apply it to the actual issue is also a key point that should be considered carefully. Referring to the related research, we decide to tool the EoP algorithm by PyCharm 2021.2 (The main program please referring the appendix). The basic flow is shown in Fig.5-53.

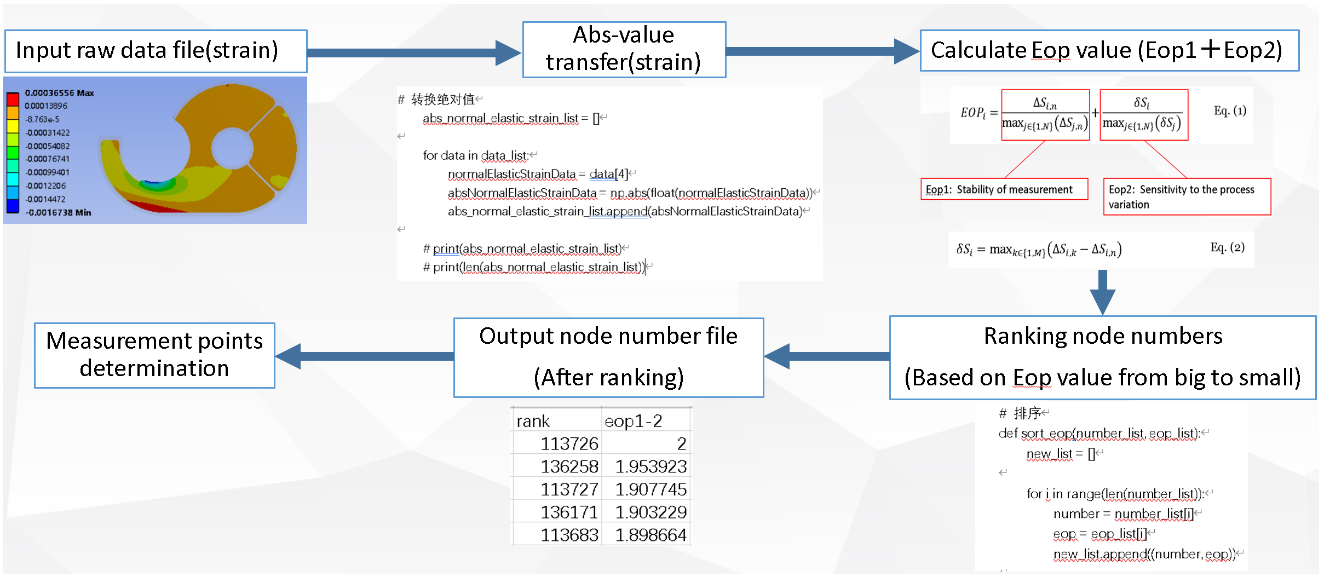


Fig.5-53 Flow chart of measurement points determination

5.4.3 Actual apply of EoP algorithm

To confirm the sensitivity in X and Y directions, we assume three fixturing situations: one correct case and the other two cases in which single fixturing rising is about 30% as listed in Table 5-10, Fig.5-54 is the sample of EoP calculation in X-axis. Based on the EoP tool, the sensitive point distribution of the X-axis and Y-axis could be shown directly in Fig.5-55. According to the following principle of Measurement points determination.

1. The hold areas cannot be selected,
2. Workpiece areas close to the thin-walled structure cannot be selected,
3. Working areas of end-milling are not allowed to be selected,
4. Surfaces of positioning reference are not preferable to measure.

The sensitive point candidates of the X-axis and Y-axis can be determined which are shown in Table 5-11 and Fig.5-56. But these points are not verified yet. In future research, several RSM optimization processes are necessary, if deformation-good points ＞ deformation-all points ＞ deformation-bad points, then verification can be confirmed.

Table. 5-10 Fixture force setting

	Fixturing force[N]	
Settings	F1	F2
Setting 1	200	500
Setting 2	300	500
Setting 3	200	750

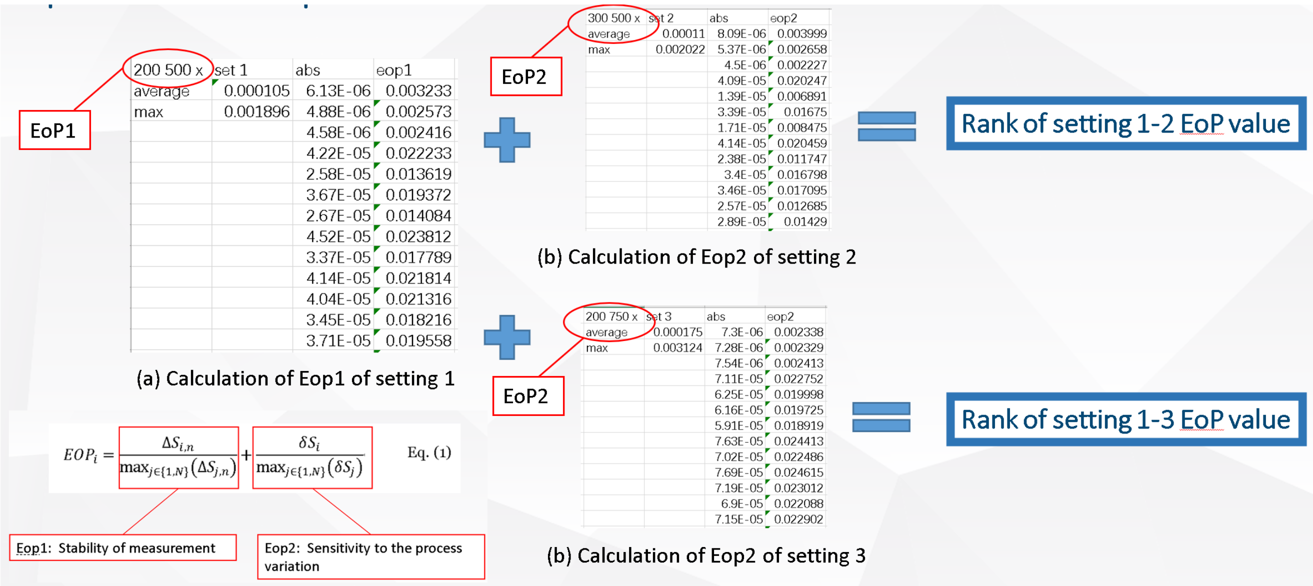
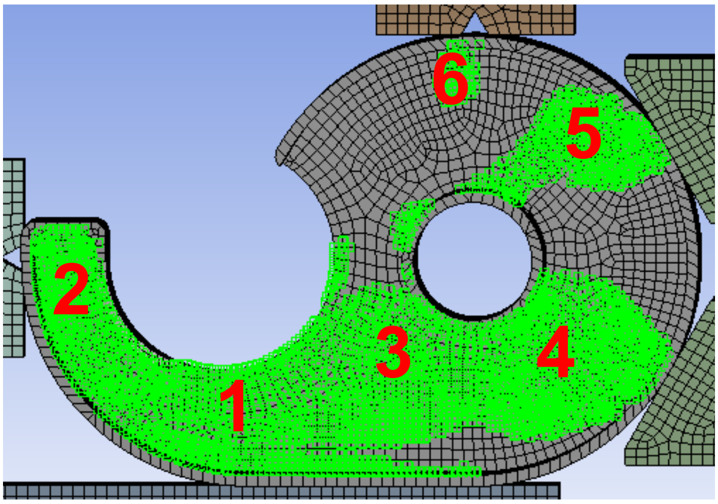
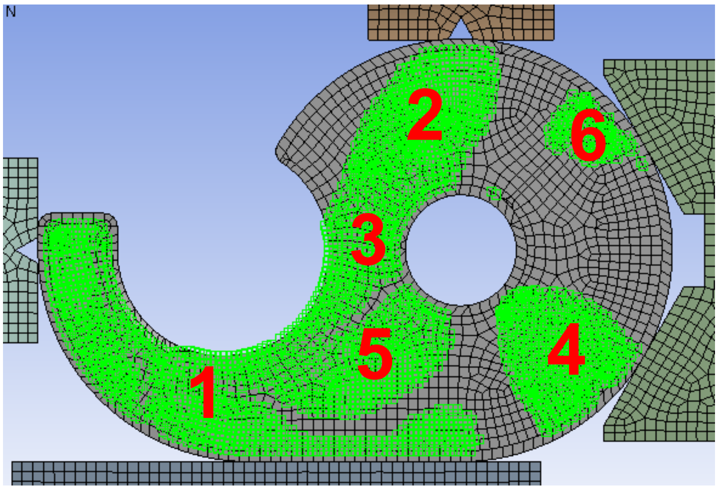


Fig.5-54 Sample of Eop calculation process in X axis



(a) Sensitive point distribution of X

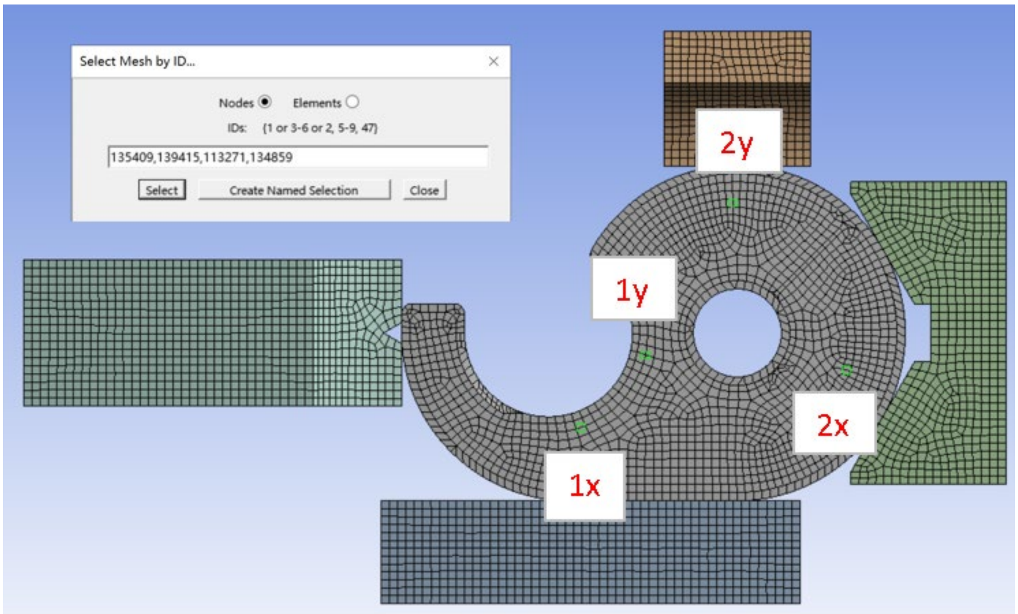


(b) Sensitive point distribution of Y

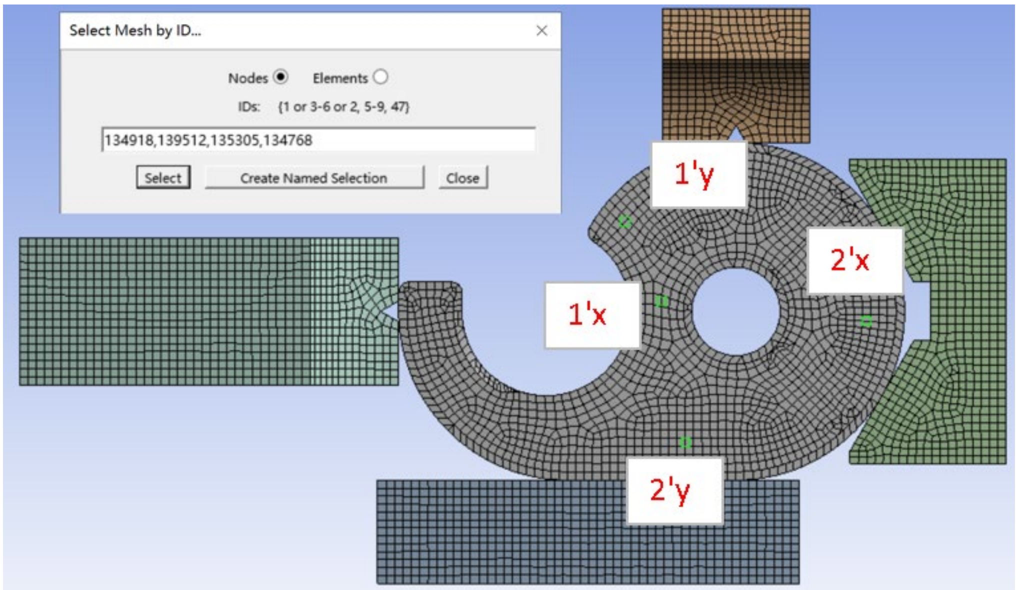
Fig.5-55 Sensitive aeras distribution

Table. 11 Fixture force setting

	X	Y
Sensitive	135409,139415	113271,134859
Unsensitive	134918,139512	114997,135305

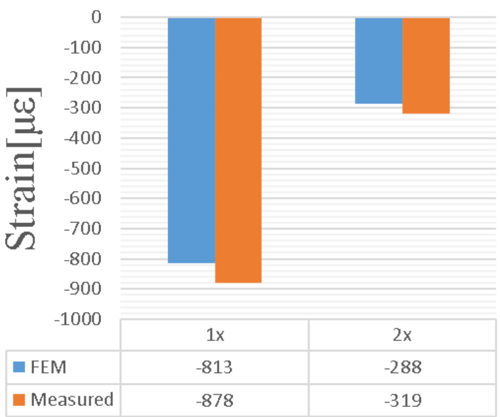


(b) Tentative sensitive point determination

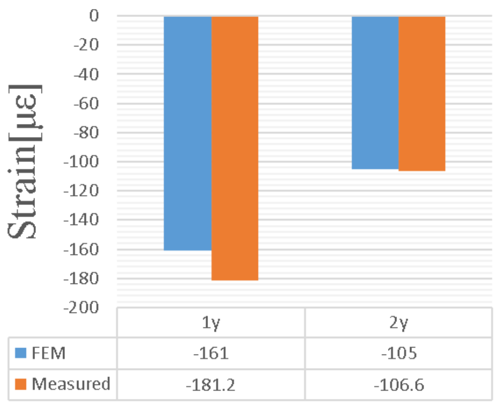


(b) Tentative unsensitive point determination

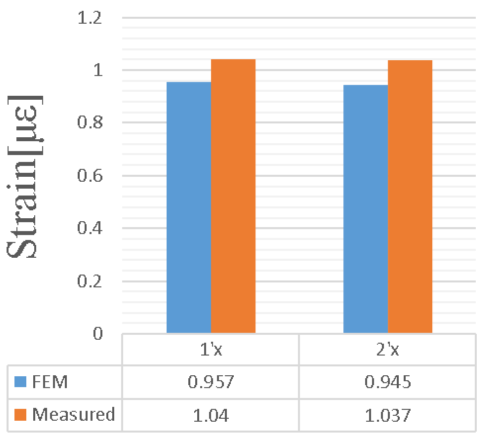
Fig.5-56 Candidate points determination



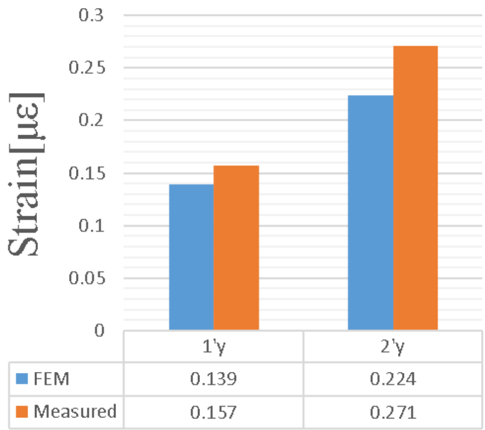
(a) Comparison of strains 1x and 2x in Setting 2



(b) Comparison of strains 1y and 2y in Setting 2



(b) Comparison of strains 1'x and 2'x in Setting 2



(d) Comparison of strains 1'y and 2'y in Setting 2

Fig.5-57 Strain comparison of candidate points

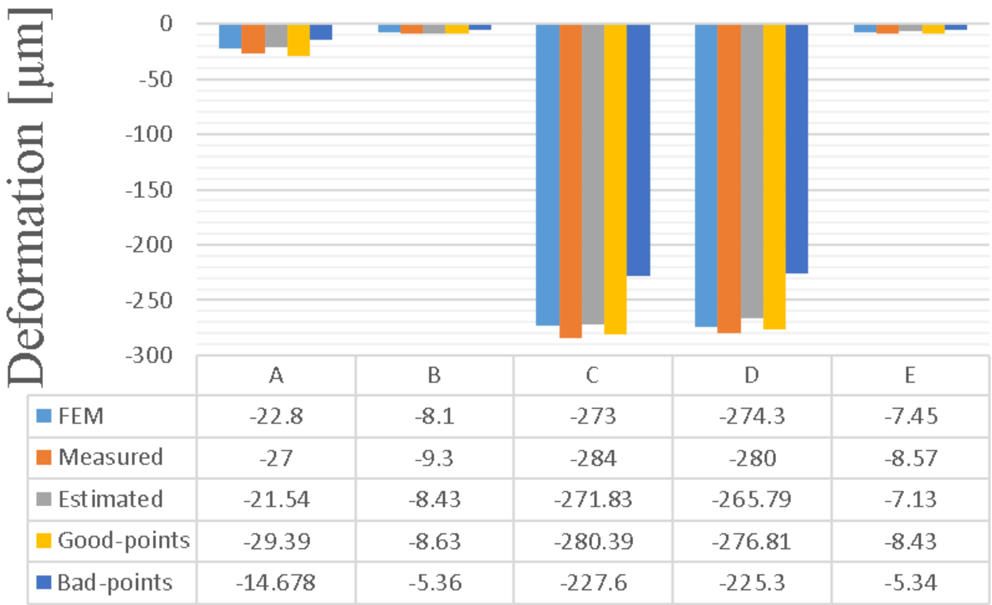


Fig.5-58 Comparison of deformations (FEM, measured estimated and good/bad points)

To evaluate the estimated deformation, corresponding workpiece deformations (dimensions A to E in Fig.5-47) calculated from estimated fixturing forces of Setting 1 to 3 are obtained. The results of setting as the sample are shown in Fig.5-57, the average difference of strain is about 10%. Comparisons of estimated deformation and measured deformation are shown in Fig.5-58, the estimated deformations with the Iteration optimization process are smaller than the measured deformations and the average difference of strain is about 26%, the deformation of good points are bigger than estimated and bigger than bad points, the difference is about 31.9%. From the results, we could see the estimated results of bad-points show insensitive deformation change with the fixturing force change. The deformation estimated results of good-points are not sensitive enough but still bigger than the estimated results of all-points. These performances met our expectations, and this also indicates the proposed method has a possibility to determine the measurement points based on the EoP algorithm.

Chapter 6
Overall conclusion

In my doctor course, the step conclusion was introduced as follows.

○ Confirm the feasibility of on-machine estimation of Standard thin-structured parts deformation (general jig). Also confirmed the feasibility of on-machine estimation of Non-standard thin-structured parts deformation (Multi-points contact jig).

- ○ The proposed method can estimate the fixturing force and workpiece deformation of the thin-walled workpiece.
- ○ The proposed method can estimate the workholding situation of the thin-walled parts under different fixture sequences.
- ○ Current research is focusing on the effect of measurement points determination.

In my master's research, I have not considered the effect of the variation of the contact friction. Therefore, in the doctor course, I research on establishing a mechanical model which describes the relationship between the fixturing force, clamping sequence of action, and friction between workpiece and fixtures during doctor course. The following research work is mainly carried out in these steps:

(1) This research focuses on the accuracy control and error control of standardized/ non-standardized fixtures for thin-walled workpieces.

(2) Through the on-machine estimation method, the strain and structural deformation can be predicted in advance during machining process.

(3) Deformations are optimized by optimizing the boundary conditions to achieve the purpose of improving machining accuracy.

(4) This research can actively cooperate with the production and processing process to lay a solid foundation for obtaining more accurate parts in the future.

(5) 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.

Acknowledgement

I first would like to express my great appreciation to Prof. Koji Teramoto for his excellent advice and diligent efforts to guide my research through my master career. Prof. Koji Teramoto is always available with his valuable suggestions and guidance throughout my master study. I will never forget the revisions he made on each of my technical papers. Without his support from various aspects, I could not make it today.

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Finally, my deep gratitude goes to my family. I thank my parents for their love and support.

Appendix

```
import csv
import numpy as np


def eop(abs_, max_abs):
    return abs_ / max_abs


def list_add(list1, list2):
    new_list = []
    for i in range(len(list1)):
        new_list.append(list1[i] + list2[i])
    return new_list

# Rank/排序
def sort_eop(number_list, eop_list):
    new_list = []

    for i in range(len(number_list)):
        number = number_list[i]
        eop = eop_list[i]
        new_list.append((number, eop))

    # Rank/排序
    # print(new_list)
    sort = sorted(new_list, key=lambda x: x[1], reverse=True)
    # print(sort)

    new_number_list = []

    for num in sort:
        new_number_list.append(num[0])

    return new_number_list



def save_to_file(out_list,name):
    save_str = ''

    for i in range(len(out_list)):
```

```
        if i > 0:
            save_str += ','
        data = out_list[i]
        save_str += data

    # Preserve file/保存文件
    out = open(name + "_out.txt", 'w')
    out.write(save_str)
    out.flush()
    out.close()


def open_file(name, ext):
    # List of preserved file
    data_list = []

    # Read file/读取文件
    with open(name + "." + ext) as f:
        reader = csv.reader(f)
        #
        count = 0
        for row in reader:
            if count != 0:
                data_list.append(row)
            count += 1
    return data_list


def get_number_list(name, ext):
    data_list = open_file(name, ext)
    number_list = []
    for data in data_list:
        number_list.append(data[0])
    return number_list


def read_file(name, ext):
    data_list = open_file(name, ext)

    # Transfer to ABS value/转换绝对值
    abs_normal_elastic_strain_list = []

    for data in data_list:
```

```
        normalElasticStrainData = data[4]
        absNormalElasticStrainData =
np.abs(float(normalElasticStrainData))

abs_normal_elastic_strain_list.append(absNormalElasticStrainData)

    # print(abs_normal_elastic_strain_list)
    # print(len(abs_normal_elastic_strain_list))


    # Maxmum value/最大值
    max_abs = max(abs_normal_elastic_strain_list)

    eop_list = []

    for value_ in abs_normal_elastic_strain_list:
        eop = value_ / max_abs
        eop_list.append(eop)
    return eop_list


eop1_x = read_file("200_500_x", "csv")

eop2_x = read_file("300_500_x", "csv")

eop3_x = read_file("200_750_x", "csv")

eop1_y = read_file("200_500_y", "csv")

eop2_y = read_file("300_500_y", "csv")

eop3_y = read_file("200_750_y", "csv")

number_list = get_number_list("200_750_y", "csv")

eop1_2_x = list_add(eop1_x, eop2_x)

eop1_2_y = list_add(eop1_y, eop2_y)

eop1_3_x = list_add(eop1_x, eop3_x)

eop1_3_y = list_add(eop1_y, eop3_y)
# print(eop_1_3_x)
```

```
#
eop_1_2_x_sort = sort_eop(number_list, eop1_2_x)

eop_1_2_y_sort = sort_eop(number_list, eop1_2_y)

eop_1_3_x_sort = sort_eop(number_list, eop1_3_x)

eop_1_3_y_sort = sort_eop(number_list, eop1_3_y)


save_to_file(eop_1_2_x_sort, "eop_1_2_x")
save_to_file(eop_1_2_y_sort, "eop_1_2_y")
save_to_file(eop_1_3_x_sort, "eop_1_3_x")
save_to_file(eop_1_3_y_sort, "eop_1_3_y")
```

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