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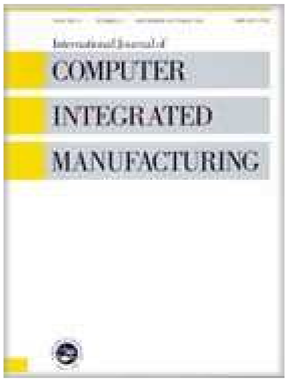

Responsive Manufacturing-A methodology for the development of machining fixtures

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A methodology for the development of machining fixtures for components with complicated geometry

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Abstract

At present, fixture design in industry is largely an experienced-based, ad-hoc process. In the case of the design of fixtures for complex components, this approach often results in a need for rework and consequent delays to production.

Machining fixture design has been the subject of considerable research efforts; however most research activities have addressed one or a small number of interactions between fixture and other manufacturing system elements.

In this paper, a novel fixture design methodology based on concurrent engineering is described. This methodology models physical space, loads, stress, deformation, thermal effects, vibration, etc., determines the loads and deflections arising from the locating, clamping and machining procedures, and estimates the resultant effects on component quality.

To assist in the development of the methodology, the high technology industrial partner originally provided the researchers with a range of complex machined components of various sizes, incorporating many different features. The methodology has been tested against a range of successful and unsuccessful fixture designs supplied by the industrial partner.

Key words: machining fixture, virtual simulations, CAD/CAM, FEA, kinematic

1 Introduction

A machining fixture is a device that holds components in a unique position rigidly for machining operations, so that a batch of components, satisfying the quality requirements, can be produced. The machining fixture is a key element of the component manufacturing system, but fixture design for components with complicated geometry is a lengthy process that includes conceptual design, detailed design and validation. Often, the performance of a fixture is very difficult to predict, as it is influenced by a large number of direct and indirect factors including workpiece shape, size, tolerance requirements, process plan, machining parameters (e.g. machining speeds and feeds), machining strategy, cutter paths and inspection strategy. The fixture design decisions rely on the designer's assessment of the effects of each factor on the specified product quality.

Typically, fixture development is still a method of trial-and-error. The more experience the fixture designer has, the fewer fixture iterations will be required. However, even when employing very experienced specialised fixture designers, non-optimal fixture performance occurs frequently. Without appropriate modelling tools and a thorough understanding of the interactions of the fixture with the manufacturing system of components, it is very unlikely that a fixture for a complex component can be correctly designed at the first attempt; this can only be achieved by considering all relevant factors concurrently at an early stage of design.

The basic requirements of machining fixture are:

- Good loading repeatability, so that mass production of components can be achieved
- Immobility: The components are held firmly such that they will not move under machining forces
- Minimal number of set-ups: The fixture makes full use of machine capability and is designed in such way that the smallest number of set-ups is required whilst the fixture performance remains satisfactory. The reduction of the number of set-ups can significantly reduce machine time and error stack-up
- Accessibility: No collision is allowed between fixture, component, machine tool and machine
- Good dynamic performance: No chatter or excessive vibration is allowed during machining of component held by a fixture
- No excessive deformation of component occurs during fixturing and machining

2 Background

A considerable amount of fixture design research employing advanced modelling tools is currently taking place, typically taking account of one or two of the earlier-stated requirements.

With regard to loading repeatability and immobility, (Asada et al 1985) derived a mathematical model of the necessary and sufficient conditions for deterministic component locating. This model makes it possible to achieve an automated, computer-generated optimised fixture locator layout. More recently, a significant amount of research using kinematic analysis to achieve optimal fixture layout has taken place. Conventionally, the contact between fixture and workpiece is often modelled as point contact. a kinematic model of fixtures was developed with consideration of underlying surface properties of locator-workpiece pairs, although the fixture and workpiece were still treated as rigid bodies (Wang 2001). Further to this, (Wang 2002) provided a kinematic model to predict the contact force of the workpiece-fixture pair using a constrained quadratic optimisation by applying the minimum norm principle. The model revealed that the passive contact force is history-dependent during a sequence of clamping and/or external force loading. A method of fixture optimisation using multi-objective functions of accurate localisation and minimal but balanced locator contact force was proposed by (Pelinescu et al, 2002). The approach required a fixture layout with the minimum number of elements, i.e. six locators and a clamp for a three dimensional space, and friction was not taken into consideration. (Ding et al 2001) presented a method for the automatic selection of fixturing surfaces and fixturing points for polyhedral workpieces by employing the constraints of form-closure and minimising the workpiece positioning error.

Deformation and vibration analyses of fixture-workpiece pairs represent another hotspot of the fixture research of last decade. Critical to the accuracy of these analyses is the model of the contact relationships between fixture elements and the workpiece. There are two commonly used methods: contact elasticity modelling (Li et al 1999 and Li et al 2001), where the workpiece is treated as an elastic body in the contact zone and rigid elsewhere, and finite element methods (Liao et al 2001, Yeh et al, 1999 and Zheng et al 2005). These modelling approaches can be used for the optimisation of locator and clamping positions and clamping force magnitude (DeMeter et al**,** 2001).

Accessibility analyses are typically based on the modelling of fixture space and its interactions with tooling space to ensure that the tool has reasonable access to the component during machining. (Kumar et al 2000 and Kow et al 2000) presented a computer-aided modular fixture design system in which the detection of machining interference was realized using the cutter swept volume approach. Simulation was conducted to detect the collision statically.

Although significant advances have been made, many of the problems have been addressed by isolating individual fixturing system issues. A fixture design that optimally satisfies a subset of fixture design criteria is unlikely to provide an optimal solution in terms of overall performance. It may result in an infeasible machining or inspection strategy. For example, the optimal locating position derived in isolation might be on the datum surface for inspection or on the approach path of the machine tool. Therefore, it is important to consider the relationships between fixtures and other elements of the manufacturing system (in particular machining and inspection processes) in the early stages of fixture design, and to conduct the development of the process plan concurrently, i.e. to take a concurrent engineering approach. The final manufacturing system should be a trade-off between a range of parameters including fixturability, machinability, testability and functionality, etc.

As implied above, most research work to-date only considers a subset of the fixture design problem, or treats fixture development as a serial process, i.e. designing the fixture prior to devising the machining strategy. Research issues concerning the interactions between manufacturing system and fixture are seldom addressed for the design of an optimal manufacturing system.

3 A concurrent fixture development methodology

A concurrent fixture development methodology, developed at the University of Nottingham, is described in this paper. The methodology enables the concurrent design of a fixture taking into account all key interaction factors (see later) and machining strategies. The methodology uses space occupancy, kinematics and engineering error analysis. The industrial collaborator that supports this research produces many complex machined components with tight tolerances. The collaborator recognises the need for a comprehensive concurrent approach to fixture design in order to ensure that delivery schedules and quality targets are met.

The development of a single hit fixture (Figure 1 (c)), for holding cast turbine blade (Figure 1(a)) to be machined to the final turbine blade (Figure 1(b)), is used as case study in this paper.

Figure. 1 Fixture development for turbine blades

3.1 Key interaction factors

Good fixture design should of course ensure component quality and manufacturability. However, it should also contribute to the achievement of maximum productivity, long tool life, low cost machining strategies, simple inspection strategies and short lead times. As shown in Figure 2, a good fixture design requires an understanding of the interactions between fixture, component, machine, tool, process planning and inspection. The factors that should be considered are discussed below.

Figure. 2 Interaction of key factors for the fixture design

Component: Components are the key input for fixture design. Fixture design should take account of quantities of components, similarities within component families, features to be machined, the geometry, size, material, etc. These factors will influence the type of fixture, the number of set-ups and the layout of the fixture. On the other side, however, after satisfying the function and quality requirements, component designs should take account of fixturability, machinability and testability issues.

Process planning: Process planning is the selection of processes, e.g. milling, turning, drilling, grinding, and the plan for the process sequence. The selection of processes is closely related to component material and the costs and efficiencies of potential machining processes. The chosen process will directly lead to the selection of a machine that is capable of that process. The selection of machine and process dictates the number of set-ups and the features that should be machined in a specific set-up.

Machining strategy: It is important to consider the effects of machining strategy on components and fixtures, in particular the potential component and fixture deformations and vibration resulting from the machining forces and the corresponding fixture clamping forces. In most current machining strategy work, the relationship between machining strategy and fixture design is ignored. As a result, the machining strategy is designed in favour of tool life and material removal rate, therefore, large machining forces leading to excessive component and/or fixture deformation are often observed and, because large clamping forces are required to balance the machining forces, these clamping forces can result in further deformations. The resultant combination of machining and clamping deformations may cause unacceptable profile errors. At the very least, tighter tolerances may have to be applied to other error sources such as process error, component variation, etc., in order to compensate for the profile errors arising from machining parameter selection.

Machine: The selection of machine depends on the processes, machine cost (or machine operating cost), component quality requirements, and availabilities of machines in the workshop, etc. The machine envelope and the number of degrees of freedom of machine movement (e.g. five-axis machining centre) are important influential factors on fixture set-up and rough space design of the fixture.

Tool selection: The factors concerning tool selection that are relevant to fixture design include tool geometry, tool size, lead in and lead out distances, and approach direction. In current practice, the tool designer tends to select the tool type and tool approach direction (to the component) to optimise tool life, without consideration of fixture requirements. This approach often leads to unnecessarily constrained space for fixture development; sometimes, this approach may result in collisions between fixture, component and tool.

Inspection: It is important to take inspection requirements into account during fixture design, in particular in-process inspection requirements. Sensors, machine probes and CMMs (coordinate measurement machines) are increasingly used to enable inspection of components when they are loaded within fixtures. However, it is seldom recognised that inspection space, tool space and fixture space share the same working space and should be conducted interactively with tool design and fixture design. As a result, the locator or clamp may be put on or near the measurement datum surfaces of components. In this case, the fixture prevents in-process inspection of certain areas, or limits the approach direction of the inspection device. The result may be longer inspection times, lower inspection accuracy or infeasible inspection strategy.

A range of virtual simulations to model the tooling, inspection and fixturing processes and their interactions at an early stage of fixture design is paramount in order to determine their impacts on component quality. A fixture development procedure with assistance of virtual simulations is shown in Figure 3. These analyses of interactions are focused on three aspects: space occupancy, kinematics, and engineering errors. The three forms of analysis are described in more detail in the following sections. The virtual simulation tools include CAD/CAM (Computer

Aided Design/Computer Aided Manufacturing) modelling, FEA (Finite Element Analysis), and kinematic numerical analysis.

Figure. 3 Procedure of fixture development in relation to virtual simulations

Space occupancy analysis is conducted first, as it provides vital information for set-up planning, enabling a decision as to the minimum number of fixtures that i required, the group of features to be machined using each fixture and the approximate sizes of fixtures and tools. Following space occupancy analysis, kinematic analysis can be carried out based on the knowledge of the features to be machined by each fixture, etc. Finally, deformation, stress, thermal and vibration analyses may be conducted depending on the circumstances.

Armed with the results of the above analyses, the designer can propose a fixture design that provides a satisfactory trade-off between the multiple requirements placed on the fixture. After fixture fabrication, a small number of components are then machined to evaluate fixture performance and verify the fixture virtual simulations.

For the case study (Single Hit fixture for turbine blades), Pro/Engineer is used for the space occupancy analysis, Matlab for the kinematics analysis, MSC.Patran for the FEA Pre/Post Process and ABAQUS for the FEA Solver. Viper grinding is chosen as the process for the turbine blades. Makino A55, a five axis machining centre that is capable of grinding process, is thus selected tentatively, subjected to the collision check. CMMs (Coordinate Measurement Machines) are used for the component quality measurement.

3.2 Space occupancy analysis

The primary tools used for space occupancy are CAD/CAM systems; in particular, these are used to conduct accessibility analysis. The goal is to ensure that there are no collisions between fixture, components, machine and tool. The space occupancy analysis includes three steps:

Step 1: Fixture space that is collision free with tool and inspection space

The fixture design for turbine blade is started from one set-up. Tool space, generated by sweeping grinding wheel along the tool trajectory, is modelled first for all the machined features. The grinding wheel is designed based on the best wheel life. Similar to tool space, the inspection space is the space that sweeps the CMM probe along the probe path. The machined features on the turbine blade F1~F15 are shown in Figure 4. The tool space and inspection space for the machined features is shown in Figure 5 (a). The trimmed remaining space, once the tool and inspection space is subtracted from the total working space, is the space for fixture as shown in Figure 5(b). An FEA of the rough fixture body designed within fixture space is necessary to evaluate the rigidity of fixture space. If inadequate, the tool space or inspection space need to be compromised.

Figure. 4 Machined features of the HP T800 turbine blade

Figure. 5: Fixture collision free space design for the T800 turbine blade (Geldart et cal 2002)

Step 2: Fixture space modification constrained by the machine envelope.

Simulations of the movement of machine tool and fixture-workpiece pair are conducted to check if any over travel problem is encountered. If yes, either tool strategy has to be compromised or the fixture space has to be reduced. For the case study, since five axis machining centre Makino A55 is used for the machine, the fixture-workpiece pair are firstly rotated around A and B axis and then moved in the z axis and grinding wheel moves in X, Y planes. Once the tool path is generated correctly for the features to be machine, over travel of machine can be evaluated.

Step 3: Fixture detailed design and collision check with machine.

This step should be undertaken in the detailed design stage of fixture after the kinematical analysis and the engineering error analysis, which suggests the optimal fixture layout and geometry of locators, clamp and supports. With detailed modelling of machine and fixture, the collision check in step 3 will verify if fixture collides with machine components. For the case study, the simulation includes the potential collision check with coolant nozzle, wheel dresser etc on the Makino A55.

3.3 Kinematic analysis

The impact of component geometry on the fixture layout is analysed by the kinematic analysis, the assumption of which is that both fixture and component are consumed to be rigid bodies.

During the kinematic fixture layout analyses, a feasible fixture needs to satisfy several basic requirements including repeatability, immobility and stability. Mathematical simulation models (using Matlab software) are used to evaluate the constraints placed on the workpiece by the fixture (including or excluding friction). Assuming frictionless contact between fixture elements (locators and clamps) and components, the component is in equilibrium under the action of clamping forces as expressed in equation (1):

$$\mathbf{G}\cdot\mathbf{F}_{\mathrm{L}} + \mathbf{C}\cdot\mathbf{F}_{\mathrm{C}} = \mathbf{0} \tag{1}$$

Where **G** is the so called fixturing matrix, $\mathbf{G} = [\mathbf{N}_{\mathrm{L}}^{1}, \cdots, \mathbf{N}_{\mathrm{L}}^{\mathbf{i}}, \cdots, \mathbf{N}_{\mathrm{L}}^{\mathbf{n}}]$, $\mathbf{N}_{\mathrm{L}}^{\mathbf{i}} = [\mathbf{n}_{\mathbf{L}}^{\mathbf{i}}$, $\mathbf{r}_{\mathbf{L}}^{\mathbf{i}} \times \mathbf{n}_{\mathbf{L}}^{\mathbf{i}}]'$, n is the number of locators, (n is three for two dimensional space and six for three dimensional space). $\mathbf{n}_{\mathbf{L}}^{\mathbf{i}}$ and $\mathbf{r}_{\mathbf{L}}^{\mathbf{i}}$ are the unit normal and positional vectors of the ith locator respectively, $\mathbf{F}_{\mathbf{L}} = [f_{\mathrm{L}}^{1}, \cdots, f_{\mathrm{L}}^{i}, \cdots, f_{\mathrm{L}}^{n}]'$, the f_{L}^{i} is the magnitudes of the reaction force on the ith locator. **C** is the clamping matrix and $\mathbf{C} = [\mathbf{N}_{\mathrm{C}}^{1}, \cdots, \mathbf{N}_{\mathrm{C}}^{\mathbf{j}}, \cdots, \mathbf{N}_{\mathrm{C}}^{\mathbf{m}}]$, m is the number of clamps. $\mathbf{N}_{\mathrm{C}}^{\mathbf{j}} = [\mathbf{n}_{\mathrm{C}}^{\mathbf{j}}$, $\mathbf{r}_{\mathrm{C}}^{\mathbf{j}} \times \mathbf{n}_{\mathrm{C}}^{\mathbf{j}}]'$, and Where $\mathbf{n}_{\mathbf{C}}^{\mathbf{j}}$ and $\mathbf{r}_{\mathbf{C}}^{\mathbf{j}}$ are the unit normal and positional vectors of the jth clamp pointing into the workpiece respectively, $\mathbf{F}_{\mathbf{C}} = [f_{\mathrm{C}}^{1}, \cdots, f_{\mathrm{C}}^{j}, \cdots, f_{\mathrm{C}}^{m}]'$, where f_{C}^{j} is the magnitudes of the jth clamp on component. Component repeatability with regard to the fixture means that the workpiece is located in a unique position, namely $\|\mathbf{G}\| \neq 0$ and the maximum locating accuracy means that maximum $\|\mathbf{G}\|$:

$$\|\mathbf{G}\| \neq 0 \text{ and } Max\,(\|\mathbf{G}\|^{2}) \tag{2}$$

Immobility requires that the six degrees of freedom are fully constrained by fixture elements (locators and clamps). For frictionless contact between fixture and workpiece, the immobility condition is that the components of $\mathbf{F}_C$ and $\mathbf{F}_L$ in equation (2) are positive:

$$\mathbf{F}_C>0 \text{ and } \mathbf{F}_L>0 \tag{3}$$

Stability means that the clamps push components to contact locators during the entire machining process, namely the reaction force on the locator is positive. The feasible clamp position is selected in terms of stability, the optimal clamping position is that where the clamps require the minimum clamping force to maintain stability. The optimisation function is written as

Minimise $$\sum_{j=1}^{m}(f_C^j)$$

Subject to $$\mathbf{G}\cdot\mathbf{F}_L+\mathbf{C}\cdot\mathbf{F}_C+\mathbf{M}\cdot\mathbf{F}_M=0 \tag{4}$$

Bounds $$0<f_L^i\ (f_L^i\in\mathbf{F}_L),\ 0<f_C^j\ (f_C^j\in\mathbf{F}_C),\ 0<f_m^n\ (f_m^n\in\mathbf{F}_M),\ 0<f_m^t\ (f_m^t\in\mathbf{F}_M)$$

Where **M** is the machining matrix of one point on the boundary of surface to be machined, and $\mathbf{M}=[\mathbf{M}^n,\mathbf{M}^t]$ and $\mathbf{M}^n=[\mathbf{n}_m^n,\mathbf{r}_m\times\mathbf{n}_m^n]'$, $\mathbf{M}^t=[\mathbf{n}_m^t,\mathbf{r}_m\times\mathbf{n}_m^t]'$.

$\mathbf{n}_m^n, \mathbf{n}_m^t$ and $\mathbf{r}_m$ are the unit normal vector, unit tangential vector and positional vector of the machining force respectively. $\mathbf{F}_M=[f_m^n, f_m^t]'$, f_m^n and f_m^t are the magnitudes of the normal machining force and tangential force respectively.

Details of the fixture optimisation based on the requirements of repeatability, immobility and stability are explained in (Wang et al 2006). Currently, the fixture layout optimisation for turbine blades is two-dimensional. Three optimal fixture layouts are generated automatically from the kinematical modelling as shown in Figure 6.

Figure. 6 Three optimal fixture layouts generated from the kinematic analyses (Wang et al, 2007)

3.4 Engineering error analysis

In order to help understanding the impacts of the machining, clamping and locating loads on component quality, finite element analyses (FEA) of static deformation, dynamic deformation and natural frequency, friction etc. are employed. For the case study, only static deformation analysis is conducted at this stage

The turbine blade (Figure 7(a)) is assumed to be elastic, and a rigid-deformable contact model (Figure 7 (b)) has been built to represent the relationship between fixture and turbine blade. The deformation of the fixture is taken into consideration by assigning a spring element to each of the locators and clamps, the stiffness of which is calculated separately (e.g. Figure 7(c)). Since the clamping forces and machining forces are often applied to the workpiece at different positions and different times, multiple FEA steps are required. In order to simulate the clamping deformation and machining procedure on a machined feature of the component, four FEA steps may be required: Step1: apply a small clamping force on the workpiece to ensure that the workpiece gently contacts the fixture locators in order to ascertain the relative position between fixture and components; Step 2: Apply the full clamping forces, the difference in the position of the component between Step 1 and Step 2 represents the clamping deformation; Step 3: Impose machining forces on a feature of the component to be machined, the position deviation between Step 3 and Step 2 is then the machining deformation; Step 4: Release the machining force, and maintain the clamping forces; Step 3 and Step 4 can be repeated if another feature is to be machined using the same fixture.

Figure. 7 Static FEA deformation analysis of fixture-turbine blade pair (Wang et al 2007)

FEA simulation of deformation can be used for the error decomposition and tolerance assignment. Surface error is defined as the maximum deviation between the nominal machined surface and the actual machined surface. If $\mathbf{E}^{\mathbf{m}}$ is the resultant surface error arising from the deformation of both the workpiece and the locators in the m direction; $\mathbf{E}^{\mathbf{m}}_{\mathbf{wp}}$ and $\mathbf{E}^{\mathbf{m}}_{\mathbf{loc}_i}$ are the surface errors resulting from the deformation of the workpiece and the i^{th} locators in the m direction respectively, and n is the number of locators, $\mathbf{E}^{\mathbf{m}}$ is written as shown in Equation (5) (Wang et al 2007)

$$\mathbf{E}^{\mathbf{m}} = \mathbf{E}^{\mathbf{m}}_{\mathbf{wp}} + \sum_{i=1}^{n} (\mathbf{E}^{\mathbf{m}}_{\mathbf{loc}_i}) \qquad (5)$$

In addition to calculating the clamping deformation and machining deformation, FEA can also be used for the machining strategy selection. For example, the machining force magnitude and sequence is different for up-grinding and down-grinding of the machining surface, the FEA output will suggest which one is better in terms of deformation. The impact of friction (between the fixture element and component) on component quality can be estimated by assigning a range of friction coefficients, which can be varied from zero (frictionless) to infinite. Details of the FEA for fixture and turbine blade are explained in (Wang et al 2007)

3.5 Industrial evaluation of the methodology

The high technology collaborator company has provided the researchers with a range of complex machined components of various sizes, incorporating many different features, in order to evaluate the effectiveness of the methodology. This has enabled all the analytical components of the methodology, i.e. space occupancy, kinematics and engineering errors, to be thoroughly tested.

The collaborator company has also provided the researchers with details of a number of its fixtures which had been developed via the conventional, experienced-based approach; several of these had required rework, resulting in delays to production. The fixture development methodology was used to analyse these fixtures. It highlighted a range of problems including (1) (single fit fixture) collisions requiring fixture modification (2) components moving within the fixture, and (3) large deformations. In the case of the reworked fixtures, the methodology identified most of the problems that had occurred and, in the case of other fixtures, it also identified areas of weakness which could result in reduced machining accuracy.

3.6 Current situation

The fixture development methodology described in this paper is near completion. It currently uses a range of commercially available software tools and is therefore not at present packaged as an integrated toolset. However, it can be used as a set of individual functions.

Although the lack of integration is to some extent a disadvantage, the methodology's utilisation of commercial, industrially-proven tools makes it attractive to our key collaborator, who has several of these tools. As a result, the company's fixture design expert is trialling the methodology, with the help of the researchers, on the design of a fixture for complex machined components. The research team awaits an industrial-based evaluation of the methodology based on this, following which a decision will be made with regard to further exploitation.

4 Conclusions

The machining fixture is a key contributor to the manufacturability of a component, and should be designed to optimise the performance of the overall machining process (including in-process inspection). However, at the present time, industrial fixture development is still largely reliant on the experience of the designer and a process of trial and error; this leads to unnecessary costs, delays and sub-optimal performance.

The fixture development methodology described in this paper is novel in that it enables the user to take account of machining strategy and all key interactions between fixture, component and other system elements at an early stage. By modelling and analysing a range of parameters including physical space, loads, stress, deformation, thermal effects and vibration, the methodology enables the user to avoid many of potential problems of conventional fixture development and to produce a near-optimal design prior to physical manufacture of the fixture.

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(a) Cast turbine blade (b) Final turbine blade (c) Single hit fixture for blades

Figure. 1 Fixture development for turbine blades

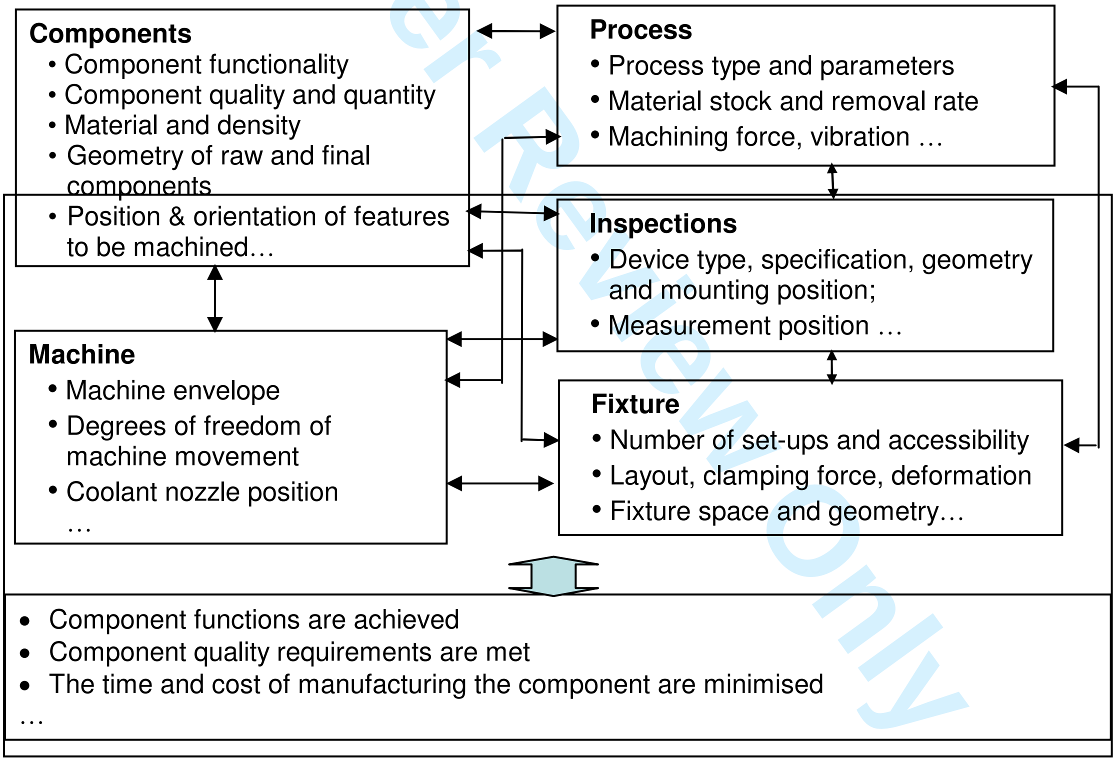


Figure. 2 Interaction of key factors for the fixture design

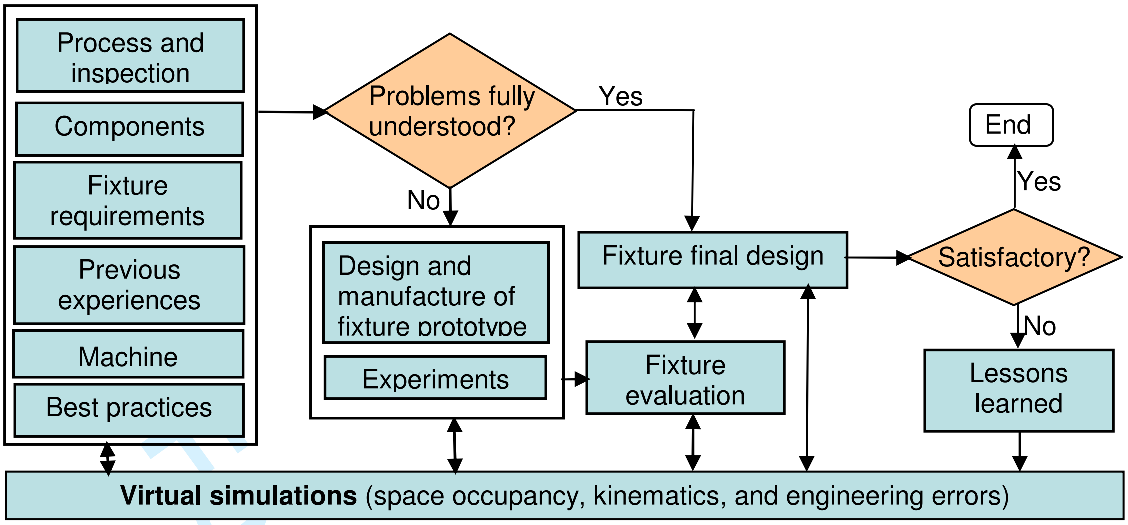


Figure. 3 Procedure of fixture development in relation to virtual simulations

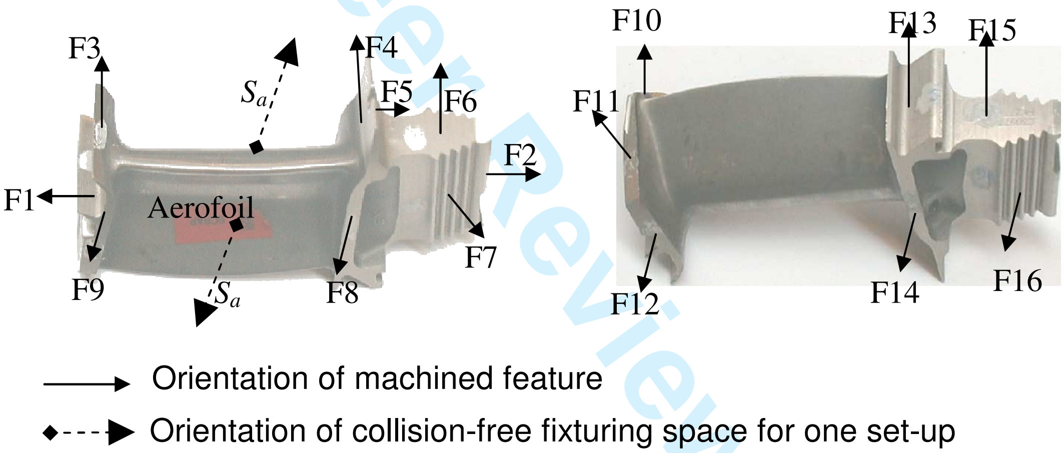
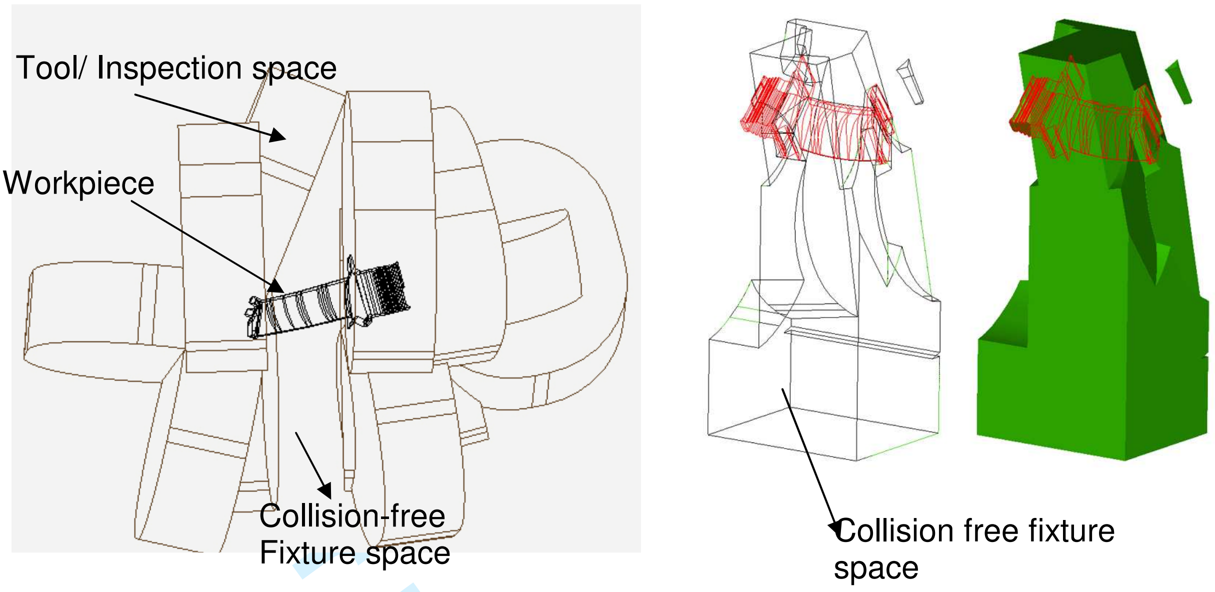
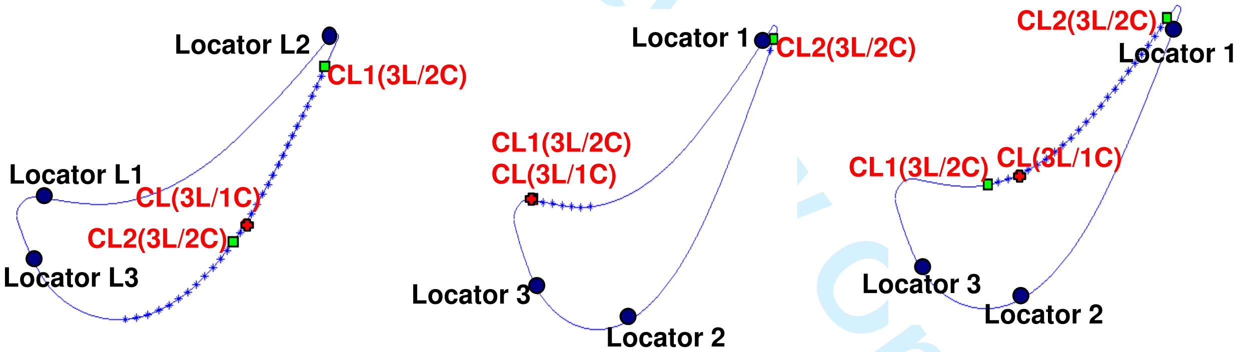


Figure. 4 Machined features of the HP T800 turbine blade



(a) Tool and inspection space (b) Trimmed fixture space

Figure. 5: Fixture collision free space design for the T800 turbine blade (Geldart et cal 2002)



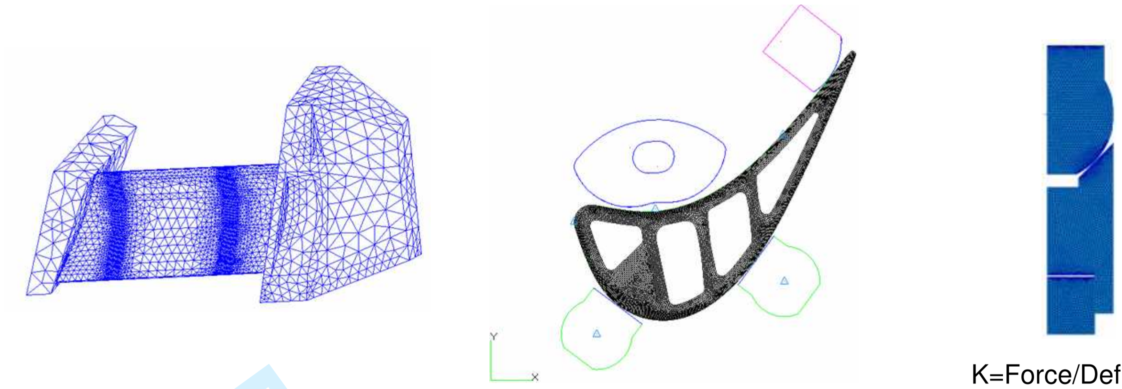
(a) The 1st fixture layout (b) The 2nd fixture layout (c) The 3rd fixture layout

● Locator * Feasible clamping position

🟥 Optimal clamping position in case of three locators and two clamp (3L/2C)

🟩 Optimal clamping position in case of three locators and one clamp (3L/1C)

Figure. 6 Three optimal fixture layouts generated from the kinematic analyses (Wang et al, 2007)



K=Force/Deformation

(a) Mesh for turbine blade

(b) Contact model between fixture and turbine blade

(c) Calculation of Fixture stiffness K

Figure. 7 Static FEA deformation analysis of fixture-turbine blade pair (Wang et al 2007)