Chapter 1

Introduction to Fixture Design

1.1   Introduction

A fixture is a device for locating, holding and supporting a workpiece during a manufacturing operation. Fixtures are essential elements of production processes as they are required in most of the automated manufacturing, inspection, and assembly operations.

Fixtures must correctly locate a workpiece in a given orientation with respect to a cutting tool or measuring device, or with respect to another component, as for instance in assembly or welding. Such location must be invariant in the sense that the devices must clamp and secure the workpiece in that location for the particular processing operation.

There are many standard workholding devices such as jaw chucks, machine vises, drill chucks, collets, etc. which are widely used in workshops and are usually kept in stock for general applications.

Fixtures are normally designed for a definite operation to process a specific workpiece and are designed and manufactured individually. Jigs are similar to fixtures, but they not only locate and hold the part but also guide the cutting tools in drilling and boring operations. These workholding devices are collectively known as *jigs and fixtures*. Figure 1.1 shows an example of a fixture commonly used on a horizontal CNC milling machine.

1.1.1   Elements of Fixtures

Generally, all fixtures consist of the following elements:

- Locators

A locator is usually a fixed component of a fixture. It is used to establish and maintain the position of a part in the fixture by constraining the movement of the part. For workpieces of greater variability in shapes and surface conditions, a locator can also be adjustable.

- Clamps

A clamp is a force-actuating mechanism of a fixture. The forces exerted by the clamps hold a part securely in the fixture against all other external forces.

- Supports

A support is a fixed or adjustable element of a fixture. When severe part displacement/deflection is expected under the action of imposed clamping and processing forces, supports are added and placed below the workpiece so as to prevent or constrain deformation. Supports in excess of what is required for the determination of the location of the part should be compatible with the locators and clamps.

- Fixture Body

Fixture body, or tool body, is the major structural element of a fixture. It maintains the spatial relationship between the fixturing elements mentioned above, *viz.*, locators, clamps, supports, and the machine tool on which the part is to be processed.
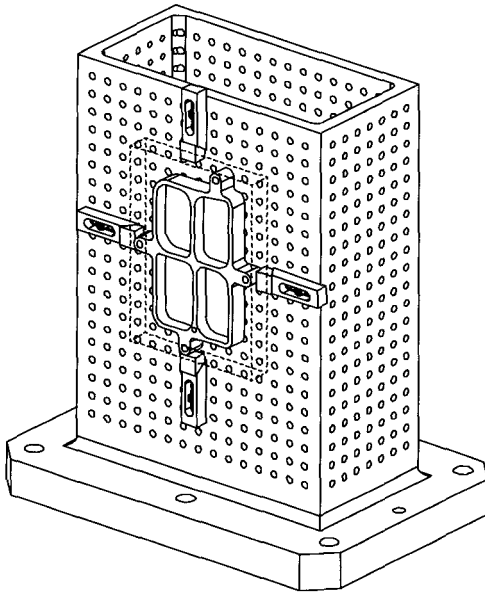

Figure 1.1 A typical 'tombstone' fixture for a horizontal CNC machine

1.1.2 Importance of Fixtures in Manufacturing

Modern manufacturing aims at achieving high productivity to reduce unit cost. This necessitates workholding devices to be efficient, *i.e.* to increase the rate of loading and unloading to speed up the manufacturing cycle time.

If t is the total time in seconds or minutes required for producing a part, then $Q = \dfrac{1}{t}$ is the number of pieces produced in unit time, or the production rate.

Considering the fact that the total manufacturing time is usually composed of:

$$t = t_m + t_h$$

where t_m is the actual machining time and t_h is the setting up and handling time, hence, the production rate is given by:

$$Q = \frac{1}{t_m + t_h} \text{ piece per unit time} \tag{1.1}$$

Supposing Q_t is the ideal production rate whereby there is no handling time loss for a given machining operation, hence we have:

$$Q_t = \frac{1}{t_m}$$

Now,

$$Q = \frac{1}{\dfrac{1}{Q_t} + t_h} = \frac{1}{1 + \left(\dfrac{t_h}{t_m}\right)} Q_t = \lambda Q_t \tag{1.2}$$

This factor $\lambda = \dfrac{1}{1 + \left(\dfrac{t_h}{t_m}\right)}$ can be termed as production efficiency.

The variation of λ with respect to Q_t is shown in Figure 1.2 for the various values of t_h. For an operation with a value of $t_m = t_h$, λ is 0.5 whereas, if $t_h = 2\,t_m$, λ is 0.33 and the production rate is reduced. Figure 1.3 shows how t_m and t_h affect production rate. It is clear from Figures 1.2 and 1.3 that

    (a) For a given t_m, reduction of t_h increases Q,
    (b) For a given t_h, reduction of t_m enhances Q.

The use of fixtures has twofold benefits. It eliminates individual marking, positioning and frequent checking before machining operation starts, thereby resulting in considerable saving in set-up time. In addition, the usage of work-holding devices saves operator labour through simplifying locating and clamping tasks and makes possible the replacement of skilled workforce with semi-skilled labour, hence effecting substantial saving in labour cost which also translates into enhanced production rate.

Furthermore, the use of well-structured fixtures with higher locating and clamping rigidity would allow for increase in cutting speeds and feeds, thereby reducing t_m, hence improving production rate.

Besides improving the productivity in terms of the rate of production, there are also other benefits accrued through the use of fixtures. They are:

(a) Increases machining accuracy because of precise location with fixtures,
(b) Decreases expenditure on quality control of machined parts as fixtures facilitate uniform quality in manufacturing,
(c) Widens the technology capacity of machine tools and increases the versatility of machining operations to be performed,
(d) Either fully or partly automates the machine tool.

1.1.3   General Requirements of a Fixture

In order to maintain the workpiece stability during a machining process, an operational fixture has to satisfy several requirements to fully perform its functions as a workholding device. The following constraints must be observed while designing a viable fixture:

• Deterministic location

A workpiece is said to be kinematically restrained when it cannot move without losing contact with at least one locator. The workpiece is constrained by a set of appropriately placed locators so that it is presentable for the machining operation. Locating errors due to locators and locating surfaces of the workpiece should be minimised so as to accurately and uniquely position the workpiece within the machine coordinate frame.

• Total constraint

A workpiece should be fully constrained at all times to prevent any movement. Clamps should provide locking forces to hold the workpiece in place once it is located. A totally restrained part should be able to remain in static equilibrium to withstand all possible processing forces or disturbance. A necessary and sufficient condition to warrant workpiece stability is to satisfy the condition of force closure.
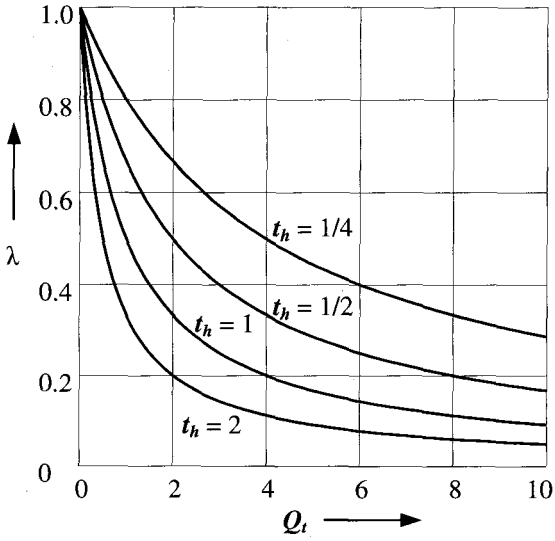
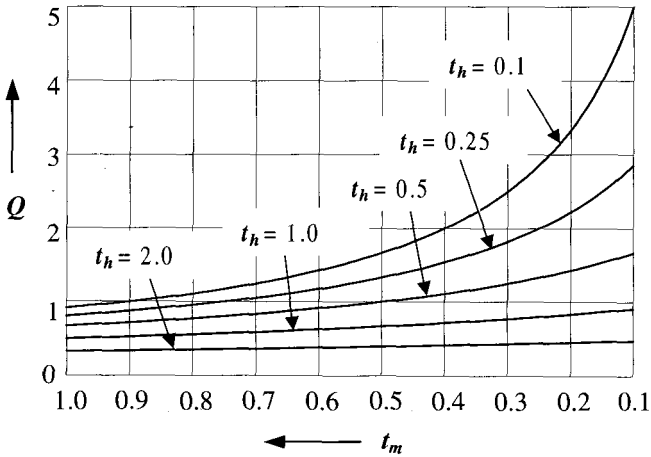*Figure 1.2 Effect of setting and handling time (t_h) on production efficiency (λ).*

Figure 1.3 Effect of handling and machining times (t_h & t_m) on production rate (Q).

- Contained deflection

Workpiece deformation is unavoidable due to its elastic/plastic nature, and the external forces impacted by the clamping actuation and machining operations. Deformation has to be limited to an acceptable magnitude in order to achieve the tolerance specifications.

- Geometric constraint

Geometric constraint guarantees that all fixturing elements have an access to the datum surface. They also assure that the fixture components do not interfere with cutting tools during a machining operation.

In addition to these requirements, a fixture design should have desirable characteristics such as quick loading and unloading, minimum number of components, accessibility, design for multiple cutting operations, portability, low cost, etc.

1.1.4   Fixture Design Fundamentals

Fixture design consists of a number of distinct activities: fixture planning, fixture layout design, fixture element design, tool body design, etc. They are listed in Figure 1.4 in their natural sequence, although they may be developed in parallel and not necessarily as a series of isolated activities in actual execution.

Fixture design deals with the establishment of the basic fixture concepts:

- Fixture layout is an embodiment of the concepts in the form of a spatial configuration of the fixture,
- Fixture element design is concerned with the concrete details of the locators, clamps and supports,
- Tool body design produces a structure combining the fixture elements in the desired spatial relationship with the machine tool.

1.1.4.1   Fixture Design

Fixture planning is to conceptualise a basic fixture configuration through analysing all the available information regarding the material and geometry of the workpiece, operations required, processing equipment for the operations, and the operator. The following outputs are included in the fixture plan:

- Fixture type and complexity
- Number of workpieces per fixture

- Orientation of workpiece within fixture
- Locating datum faces
- Clamping surfaces
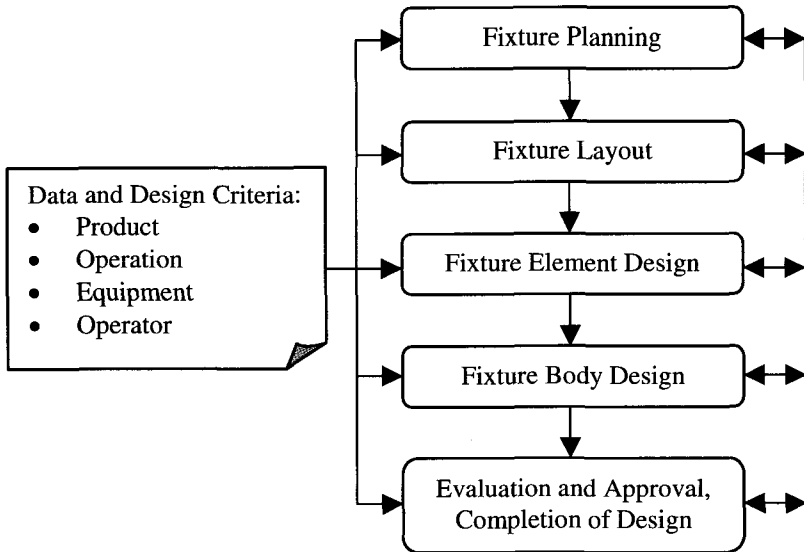- Support surfaces, if any

Figure 1.4 Various aspects of fixture design

Generation of fixture layout is to represent the fixture concepts in a physical form. The following outputs are included in the fixture layout:

- Positions of locators
- Positions of clamps
- Positions of supports, if any
- Type of locators
- Type of clamps
- Type of supports
- Clamping forces and sequence

Fixture element design is either to detail the design drawings committed on paper or to create the solid models in a CAD system of the practical embodiment of the conceptual locators, clamps and supports. It is possible to use standard designs or proprietary components. The following outputs are included in the fixture element design:

- Detailed design of locators

- Detailed design of clamps
- Detailed design of supports, if any

Tool body design is to produce a rigid structure carrying all the individual fixture elements in their proper places.

1.1.4.2 Fixture Design Criteria

The following design criteria must be observed during the procedure of fixture design:

- Design specifications
- Factory standards
- Ease of use and safety
- Economy

1.1.4.3 Fixture Design Procedure

In the design of a fixture, a definite sequence of design stages is involved. They can be grouped into three broad stages of design development.

Stage One deals with information gathering and analysis. These include product analysis such as the study of design specifications, process planning, examining the processing equipment and considering operator safety and ease of use. In this stage, all the critical dimensions and feasible datum areas are examined in detail.

Stage Two involves the consideration of clamping and locating schemes. A clamping scheme is devised in such a way that it will not interfere with the tools or cutters and are fully compatible with proposed locating surfaces or areas. The locating scheme, using standard elements such as pins, pads, etc. is designed to be consistent with clamping and tool-guiding arrangements.

Stage Three is the design of the structure of the fixture body frame. This is usually built around the workpiece as a single element which links all the other elements used for locating, clamping tool-guiding, etc. into an integral frame work.

The above procedures are quite general and can be modified depending on the relative importance of the various elements in providing for the required accuracy of the workpiece to be located and secured into the fixturing device. With the popular adaptation of modular fixturing elements, the fixture body frame is usually a standard block with fixed arrays of locating and fixing holes or slots. It becomes a matter of selecting the most suitable body frame to accommodate the various elements, provide good support of the workpiece and access to cutters and tools. Figure 1.1 shows a 'tombstone' body frame commonly used in horizontal CNC milling machines.

1.2   Locating Principles

1.2.1   Introduction

One of the principal purposes of a machining fixture is to locate the workpiece surfaces for performing a machining operation. This is usually done with respect to a number of factors to be considered such as the reference datum, supporting surfaces, features that are likely to obstruct the tool movement or access direction, etc. In general, the following surfaces should be distinguished:

- Active surfaces

These are surfaces to be machined, *i.e.* surfaces which are subjected to the action of cutting tools.

- Supporting and locating surfaces

These are surfaces by means of which the workpiece is to be located with respect to set-to-size cutting tools.

- Clamping surfaces

Clamping surfaces are subjected to the clamping forces for obtaining invariant location. Clamping surfaces are usually not finish-machined surfaces as clamping marks could damage the finish.

- Datum surfaces

Datum surfaces are reference surfaces where the dimensions are to be maintained and measured.

- Free surfaces

Free surfaces are surfaces not involved in the set-up for the particular machining operation.

1.2.2   Restrictions on the Degrees of Freedom of a Workpiece

A workpiece, just like any free solid body, has six degrees of freedom (some researchers have referred this to the twelve degrees of freedom by considering the +/- movements in each category):

- Three rectilinear displacements along the mutually orthogonal co-ordinate axes
- Three angular displacements with respect to the same axes.

During a set-up, it is necessary to restrict certain degrees of freedom so as to locate and orient the active surfaces with respect to the cutting tools. Since supporting or restricting surfaces may vary from the true geometrical shape, especially on rough-machined surfaces or cast blanks, it is desirable that the workpiece be located with respect to the point supports.

Locating using point supports in the form of hemi-spherical rest buttons would considerably reduce the influence of geometrical variations of locating surfaces on the locating accuracy. For prismatic parts, the general principle of 3-2-1 location is most commonly employed. For achieving greatest stability, the first three points of location on the primary surface should be as far apart as possible, or the area enclosed by the three points as large as possible.

For larger cast workpieces, the 4-2-1 locating principle is frequently used. Since this violates the locating constraints, one of the locating points would need to be an adjustable one. However, it is also a good practice for larger castings to be designed with accurate fixturing points. These points are subsequently removed after the first few surfaces have been machined.

For cylindrical workpieces, three-point location cannot be obtained because of the non-existence of plane surfaces, V-locators and close-fitting bushes are often used instead. For circular laminae, location can be achieved with the aid of a slot-support.

When a workpiece is required to be located with respect to an inside hole or bore, a plug is used for locating the workpiece. Locating from two holes typically uses a full and a diamond plug combination, with the latter inserted in the larger of the two holes.

The details of the principles of location can be easily found in general texts on fixture design (Henriksen, 1973) and will not be repeated here.

1.3   Clamping Principles

1.3.1   Introduction

In every machining operation, clamping of workpieces is an essential requirement. A clamp can be defined as a device for providing an invariant location with respect to an external loading system. In other words, the process of clamping induces a locking effect which, through frictional or some other forms of mechanism, provides a stability of location which cannot be changed until and unless external loading is able to overcome the locking effect. Hence, when a cutting force is producing a load or moment on the workpiece, it is necessary that a sufficient clamping force must be exerted to withstand such actions. The creation and

retention of locking effect against external loads are the principal objectives of any locking devices. The generalised requirements of locking elements can be summarised as:

- To provide a suitable locking for achieving the stability of location,
- To produce sufficient frictional effects for the above purpose but without causing any undesirable effects to the workpiece such as distortion or surface damage.

It is also essential that the idle time involving loading, locking, unlocking and unloading of workpieces should be minimised as much as possible to reduce the overall set-up and non-machining time. Certain additional requirements are therefore to be fulfilled with respect to clamping devices:

- The clamping devices must be easy to manipulate manually or otherwise,
- These devices must be quick-acting so as to reduce time for setting the clamping and simultaneous locating,
- They must be low-cost so that their application in small lot sizes is economical.

1.3.2 Basic Principles of Clamping

1.3.2.1 Orientation of Locators vis-à-vis Clamping Force

It is necessary in all clamping devices that the clamping forces hold the workpiece in its located position and should not cause any positional displacement or excessive distortion under the action of the clamping forces.

Clamping forces should be directed towards supporting and locating elements on overhanging or thin sections of the workpiece. In addition, the force should be transmitted to the rigid sections of the body frame of the fixture.

Cylindrical workpieces located in V-blocks can be clamped using another V-block, making a 4-point clamping, or clamped in a 3-jaw chuck, in a 3-point clamping configuration. The latter is usually more common, especially in turning operations.

1.3.2.2 Effect of External Forces on the Clamping Action

Clamping elements can be classified in accordance with their force-deflection characteristics. There are two broad sub-divisions, *viz.*:

- Type I: clamping elements in which the elastic deformation increases with clamping force, such as screws, levers, cams, etc.,

- Type II: clamping elements in which the clamping force assumes a constant value independent of the elastic deformation at the contact surfaces such as fixtures operated with hydraulic or pneumatic pressures.

Within the elastic region, clamping elements based on elastic deformation, *i.e.* Type I clamps, would exhibit a linearly increasing clamping force in proportion to the deformation of the clamping element, if the workpiece or the locator is assumed to be rigid. If the workpiece or locator deforms, it will cause a relaxation of the clamping element and the clamping force will decrease. A limiting case arises when the clamping is lost and the force becomes zero.

In Type II clamps, the clamping force remains constant at pre-set values and is independent of workpiece and locator deformation. This type of clamping device is therefore more reliable and would not relax over time.

1.3.2.3 Types of Clamps

Clamping elements may be either manually operated or actuated by pneumatic, hydraulic or a combination of other power facilities. They are also classified according to the mechanism by which a mechanical advantage is attained. The two basic classes include:

- Application of inclined plane theory, *i.e.* wedges, screws, cams, etc.,
- Application of lever principle, *i.e.* levers, toggles, etc.

Manual clamping of workpieces has the following disadvantages:

- Each workpiece is clamped with varying force,
- It is difficult to determine the required force for reliable clamping,
- Fatigue of operator due to manual clamping takes place,
- Time required to actuate manual clamping is longer compared to power-actuated clamping,
- Comparatively small amount of force is available without large force amplification devices.

Pneumatic and hydraulic clamping devices have eliminated most of the above disadvantages but at much higher cost as well as greater demand for space requirement and maintenance. Justification would be a balance between cost, efficiency, accuracy, operator safety and comfort. As will be explained in the subsequent sections of this book, clamping with such devices forms the basis of variable-force clamping, which is very useful in controlling the intensity of the clamping force during a machining operation and helps to reduce workpiece deformation.

For the design of non-standard clamping devices, the most comprehensive source of information can be found in a resource book, *Jigs and Fixtures: Non-Standard Clamping Devices* (Grant, 1967).

1.4   Automation in Fixture Design

1.4.1   The Need for More Flexible Fixtures

With the advent of CNC machining technology and the capability of multi-axis machines to perform several operations and reduce the number of set-ups, the fixture design task has been somewhat simplified in terms of the number of fixtures which would need to be designed. However, there is a need to address the faster response and shorter lead-time required in designing and constructing new fixtures. The rapid development and application of Flexible Manufacturing System (FMS) has added to the requirement for more flexible and cost-effective fixtures. Traditional fixtures (dedicated fixtures) which have been used for many years are not able to meet the requirements of modern manufacturing due to the lack of flexibility and low reusability. The replacement of dedicated fixtures by modular and flexible fixtures is eminent in automated manufacturing systems, due to much smaller batch sizes and shortened time-to-market requirement.

Modular fixtures are constructed from standard fixturing elements such as base-plates, locators, supports, clamps, etc. These elements can be assembled together without the need of additional machining operations and are designed for reuse after disassembly (Nee *et al.*, 1995). The main advantages of using modular fixtures are their flexibility and the reduction of time and cost required for the intended manufacturing operations. Automation in fixture design is largely based on the concept of modular fixtures, especially the grid-hole-based systems, due to the following characteristics:

- Predictable and finite number of locating and supporting positions which allow heuristic or mathematical search for the optimum positions,

- Ease in assembly and disassembly and the potential of automated assembly using robotic devices,

- Relative ease of applying design rules due to the finite number of element combinations.

A typical modular fixture constructed from the grid-hole-based system is shown in Figure 1.5.
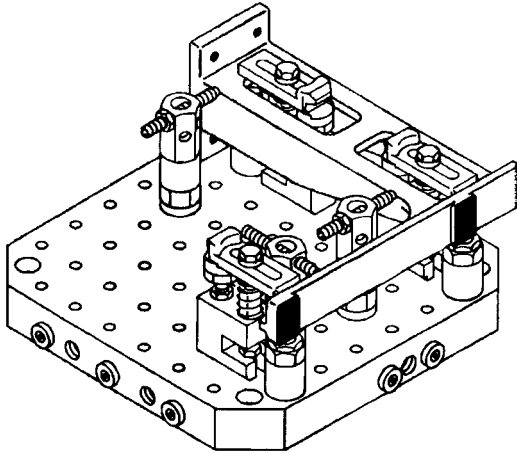
Figure 1.5 A fixture constructed from modular elements (Courtesy of IMAO Corp.)

1.4.2   Computer-aided Fixture Design Research

Fixture design research employing computer aids started in the late 1970s and early 1980s. In the initial years, interactive and semi-interactive fixture design techniques were built on top of commercial CAD systems and expert system tools. These approaches were mainly concerned with fixture configuration and there was little analysis on the other aspects such as workpiece-fixture-cutting tool interactions.

A comprehensive fixture research plan should involve the analysis at different computational levels, *viz.,* geometric, kinematic, force and deformation analyses. The following sections will present brief overviews of the research activities in each of the above-mentioned areas, followed by the need to design an intelligent fixture which can be integrated with the machine tool. This is also the aim of the main sections of the book.

1.4.2.1   Geometric Analysis

Geometric analysis is closely associated with fixture planning and spatial reasoning. It determines the selection of the type and number of fixturing elements, support and locating elements, the order of datum planes, etc. The analysis also includes the checking of interference between workpiece and fixturing elements, as well as cutting tools.

Most of the early fixture research involved geometric analysis and synthesis of fixture construction with relatively little attention to kinematic and deformation analysis.

Some of the earlier research works are briefly described. (Gandhi and Thompson, 1986) proposed a methodology for the automated design of modular fixtures. Some of the semi-automated systems were developed by (Jiang *et al.*, 1988), (Grippo *et al.*, 1987) and (Markus, 1988). (Nee and Senthil kumar, 1991) developed an automated fixture design system that integrates CAD with an expert system shell. Other systems using a 3-D solid modeller, an expert-system shell and a rule-based technique have been reported by (Lim and Knight, 1986), (Nnaji *et al.*, 1988), (Nnaji and Lyu, 1990), and (Ngoi *et al.*, 1990). These systems are capable of automatically generating partial or complete fixturing solutions for simple prismatic workpieces, based mostly on geometric analysis. Several of the above systems are based on modular fixtures.

1.4.2.2 Kinematic Analysis

Kinematic analysis is used to determine whether a fixture configuration is able to correctly locate and provide complete constraint to a workpiece.

Previous work on fixture design automation offers relatively little consideration in providing a comprehensive fixture-element database and effective assembly strategies for the generation and construction of modular fixtures. The assembly of modular fixtures is to configure the fixture elements such as locators, clamps and supports (in most cases, accessory elements are needed to generate fixture towers to fulfil the fixturing functions) on the base-plate according to a fixturing principle (e.g. 3-2-1 principle as outlined in Section 1.2.2). The determination of the locating, supporting and clamping points for the assembly of modular fixtures is a key issue in fixture design automation. (Trappey and Matrubhutam., 1993) proposed a heuristic approach using the projected envelope of a workpiece to determine the locating and clamping points. This method reduces the complexity of fixture configuration and could be feasible for non-prismatic parts, but the system does not consider the size of the modular fixture elements and interference between the elements, the machining envelope and the workpiece. (Chou, 1994) employed the geometric reasoning method to determine the locating and clamping points, but a detailed assembly method has not been proposed. (Whybrew and Ngoi, 1992) proposed a method using the spatial representation technique for automatic assembly of modular fixturing elements. The system uses a T-slot modular fixture system, however, the positions and types of locating, clamping and supporting elements are given as the inputs to the system. Treating a machined workpiece as a rigid body, (DeMeter, 1994a & 1994b) applied restraint analysis to a fixture with frictionless or frictional surface contacts and a linear model for predicting the impact of locator and clamp placement on workpiece displacement throughout machining operations.

In modular fixture design and assembly, particularly for a hole-matrix system, the exact points of locating, supporting and clamping should not be pre-determined as inputs before actual assembly. Since the fixture elements may not fit directly onto the tapped and location holes, it would be more difficult and sometimes not feasible to assemble the fixture elements properly. Hence, it is preferable to determine the configuration of the fixture from an assembly viewpoint.

1.4.2.3   Force Analysis

In a machining fixture, different forces are experienced, *viz.*, inertial, gravitational, machining and clamping forces. While the first three categories of forces are usually more predictable, clamping force can be rather subjective in terms of magnitude, point of application as well as sequence of application.

It has been widely accepted that a thorough analysis of all the forces involved in a fixture is a formidable task since it is an indeterminate problem with a large number of fixturing elements. When friction is taken into account, the problem becomes even more complex because both the magnitude and the direction of the static friction forces are unknown. (Lee and Haynes, 1987) reported that friction is the predominant mechanism for workpiece holding in most fixturing applications.

Even with the same fixturing forces, the force distribution in fixtures may vary significantly with different application sequence of clamping forces (Cogun, 1992). (Mittal *et al.*, 1991) and (Nnaji *et al.*, 1990) ignored the friction forces in their analysis. This simplification would lead to higher than necessary fixturing forces.

To analysis friction, (Lee and Cutkosky, 1991) constructed the limit surface in force/moment space as a convenient formalism to check the stability of the parts and to specify clamping forces. This method requires a search in the infinite clamping plane, and lacks theoretical sufficiency and is rather inefficient. When used for 3D analysis that is usually required for most fixturing configurations, this method is too complex and time-consuming to be applied. (Fuh and Nee, 1994) assumed the workpiece fixture as perfectly rigid bodies in frictional contact. (Gui *et al.*, 1996) employed linear springs to approximate the stiffness characteristics of contact between workpiece and fixture for minimising workpiece location error by optimising clamping force. (Jeng *at al.*, 1995) proposed a method to analyse the minimum clamping forces derived from the correlation between cutting force and clamping moment. This method increases the search efficiency by pruning inadequate search directions. Several stability criteria were set up after theoretical derivation, but these conclusions are correct for the force analysis with only one clamping plane. (Tao *et al.*, 1999a & 1999b) proposed a computational geometry approach to optimum clamping synthesis of machining fixtures. (Mannan and Sollie, 1997) designed a force control clamping system using feedback control and it provides an effective means for a variable force clamping system. (Li and Melkote, 2000) reported a minimum clamping force algorithm for machining fixtures.

1.4.2.4   Deformation Analysis

Due to the complexity of force interaction, workpiece deformation can be attributed to a combination of factors. Firstly, a workpiece would deform/displace under high cutting and clamping forces. Secondly, a workpiece could also deform/displace if the support and locating elements are not rigid enough to resist the above-mentioned forces. In the present analysis, it is assumed that workpiece deformation is largely due to the first cause mentioned above.

The most commonly used method in analysing workpiece deformation and fixturing forces is the finite-element method. (Lee and Haynes, 1987) and (Pham and Lazaro, 1990) studied the deformation of the workpiece, the clamping forces of the fixturing elements, the stress distribution and other characteristics of the fixturing system by modelling the workpiece as a deformable body. Although FEM can help understand the behaviour of the workpiece fixtured, it may not be a good choice for some applications due to its complexity.

1.4.3   Novel Clamping System Design

A good fixture design is critical to the quality of the finished workpiece in terms of dimensional accuracy, form precision and surface finish. One of the essential considerations in designing a good workable fixture is the generation of clamping configuration that includes the clamp placement, clamping sequence, and clamping intensities. Placing the clamps in wrong positions may disturb the equilibrium of the workpiece on the locators, resulting in the lost position of the part. Likewise, using an inadequate clamping intensity may give rise to slippage and/or lift-off of the workpiece during the machining process. On the other hand, an application of excessive clamping forces would result in excessive deflection and high contact deformation of the workpiece. In short, a poor clamping layout could cause the final accuracy of the workpiece to be out of the specified tolerances and bring about unnecessary rejects.

A less addressed research area is the performance of a fixture during machining in terms of its dynamic response and deformation. The issue is to guarantee machining accuracy through the proper control of workholding operation during machining. Therefore, a best approach to the fixturing problem is to integrate optimal fixture design with optimum fixturing execution in a unified approach.

This book devotes much effort on the development of an intelligent fixturing system (Nee *et al.,* 2000). This system provides sensory feedback and on-line fixturing control strategy to perform an optimal workholding operation. Being an important part of the "live" fixture, a novel dynamic clamping actuator capable of providing time-varying clamping intensities has been implemented. Comparative experiments are carried out to investigate the effects of the dynamic fixturing nature of the system on workpiece quality. Measured geometric errors are compared with and without using the dynamic clamping forces.

1.5   Summary

This chapter presents a brief introduction to the general and classic principles of fixture design. These principles are still very applicable and form the basis of good fixture design despite the rapid advancement of machine tools and manufacturing technology. As there are many classic texts dealing with the principles of location, clamping, and tolerance analysis of fixture design, these topics will not be covered in depth here and the readers are referred to such texts in the Bibliography.

With reduced time-to-market and smaller batch size, the use of dedicated fixtures has been steadily replaced with reconfigurable and reusable modular fixtures. Modular fixtures take a shorter time to configure and assemble, reduce inventory holding, and offer good repeatability and accuracy. They are invaluable in prototyping and proof-of-concept designs of new products. More importantly, they readily lend themselves to computerisation in design, analysis and assembly. Much of the automation in fixture design and analysis has been based on modular fixtures and this will continue to evolve in the future. Active research in this area has contributed much design knowledge and rules in fixture automation in the last 20 years. This chapter summarises some of the major contributions made by the fixture research community at the time of writing.

An ideal fixture should not only provide the machining repeatability and high productivity, it should also offer a solution which reduces workpiece distortion due to clamping and machining forces. The remaining sections of this book provide an in-depth analysis of this topic, which has not been addressed in depth previously.

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