11

Workholding—Fixtures and Jigs

Workholding in manufacturing is the immobilization of a part (workpiece) for the purpose of allowing a fabrication or an assembly process to be carried out on it. The term fixturing is also commonly used to describe workholding. Design of workholding devices normally falls within the domain of expertise of tool designers, who decide what fabrication or assembly tools to use as well as what fixtures or jigs to employ. The overall objective is to increase productivity through increased rates of manufacturing: utilize tools with appropriate lengths of life and fixtures/jigs with optimum accuracies.

A jig is a workholding device, primarily used in hole fabrication, for locating and holding a workpiece and guiding the production tool (e.g., a bushing for guiding a drill bit and thus preventing slippage and vibrations during the engagement of the tool with the workpiece). A fixture, on the other hand, is a workholding device used in machining and assembly for securely locating and holding the workpiece without providing a built-in guidance to the manufacturing tool. Both types of devices, jigs and fixtures, must provide maximum accuracy (including measures to prevent incorrect workholding) and be designed for ease of mounting and clamping of the workpiece by humans or robots.

Design of a workholding device requires a careful examination of the workpiece (geometry, material, mechanical properties, and tolerances), the fabrication processes (tool paths, machining/assembly forces, and environment, e.g., coolant liquids), and the specific machines to be utilized. An additional issue to be considered is the target setup cost that can be afforded. Owing to their complexity and high accuracy, workholding devices can be very expensive. Normally, these one-of-a-kind devices are expected to be used for a large number of workpieces in mass production, in order to minimize their per part cost. In case of small-batch or one-of-a-kind product manufacturing, modular fixtures that can be reconfigured according to the part geometry at hand should be utilized.

Although modular fixtures have been in existence since the 1940s, their primary users until the early 1980s were the machine-tool manufacturers, who fabricated small-batch or one-of-a-kind lathes, milling machines, and so on. With the widespread utilization of flexible manufacturing strategies in the past two decades, such reconfigurable devices have become very attractive in group-technology-based workcells for the fabrication of a family of similar parts. In parallel to industrial advancements on the design of modular fixtures, numerous academic research centers have also developed (1) reconfigurable and programmable ("flexible") fixtures for use in automated environments, and (2) computer-aided design tools for the efficient design of fixtures (one-of-a-kind or modular) in concurrent engineering environments.

In this chapter, following the description of general workholding principles and basic design guidelines for jigs and fixtures, we will review the use of such devices in manufacturing, in the form of dedicated or modular configurations. We will also present a brief discussion on the computer-aided design aspects of fixture/jig development.

11.1 PRINCIPLES OF WORKHOLDING

The design of a workholding device is governed by the geometry of the workpiece and the dynamics of the manufacturing process in which it is expected to participate. The fixture/jig must be able to hold the workpiece in place (i.e., preventing motion and deflections) while it is subjected to external forces. These forces are most prominent in metal cutting operations and might cause the workpiece to break away from the workholding device or to fracture if it were not supported suitably. Thus locating and clamping will be discussed below in greater detail.

11.1.1 Locating

A solid body has six degrees of freedom (dof) of mobility in unconstrained three-dimensional space: three degrees of translational movement freedom (D_x, D_y, D_z) and three of rotational movement freedom (R_x, R_y, R_z)

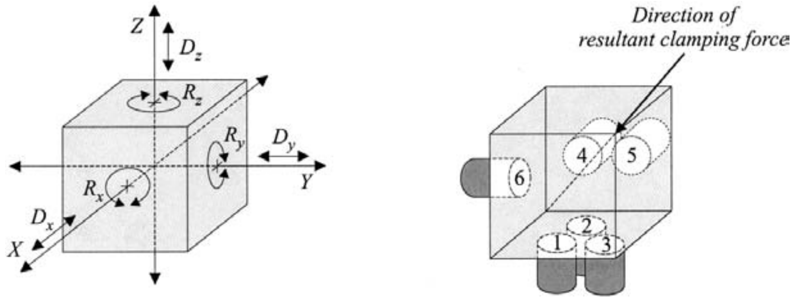

FIGURE 1 (a) Mobility of a solid body; (b) the 3-2-1 principle.

(Fig. 1). The objective of a workholding device is to eliminate all mobility and simultaneously provide adequate support to the workpiece to counteract external forces.

Three-dimensional mobility can be prevented by utilizing six points of constraint, by the 3-2-1 rule (Fig. 1b): three points (1, 2, and 3) provide a planar constraint, eliminating two rotational (R_x and R_y) and one translational (-D_z) dof, two additional (orthogonal) points (4 and 5) eliminate one more rotational (R_z) and one more translational (-D_x) dof and, finally, a sixth point (6) totally constrains the workpiece by eliminating the last translational dof (-D_y). Naturally, as seen from Fig. 1b, this immobility can be achieved only if the workpiece is pushed against these support points and held in place by a clamping device.

For the best possible accuracy, locators should contact the workpiece on its most accurate surfaces (versus unmachined, rough surfaces). Although point contact would yield best positioning accuracy, most locators have planar contact surfaces, in order to minimize damage to the workpiece due to potentially high-pressure contact points. Redundancy in locating should be avoided, unless necessary for safety reasons or to prevent deflections. Distribution and configuration of the locators is an engineering analysis issue: mechanical stress analysis should be carried out for the optimal placement of locators (Sec. 11.4).

Locators are manufactured separately from the main body of the workholding device (e.g., a mounting plate) using tool-quality-hardness steel for minimum wear. They are normally fabricated to exact specifications as fixed dimension components or as adjustable height locators. Some exemplary locators are shown in Fig. 2.

Locators may be placed on the periphery of the object or underneath it and, occasionally, fitted into existing holes on the workpiece. One must note that, for example in machining, locators should not be mounted directly on

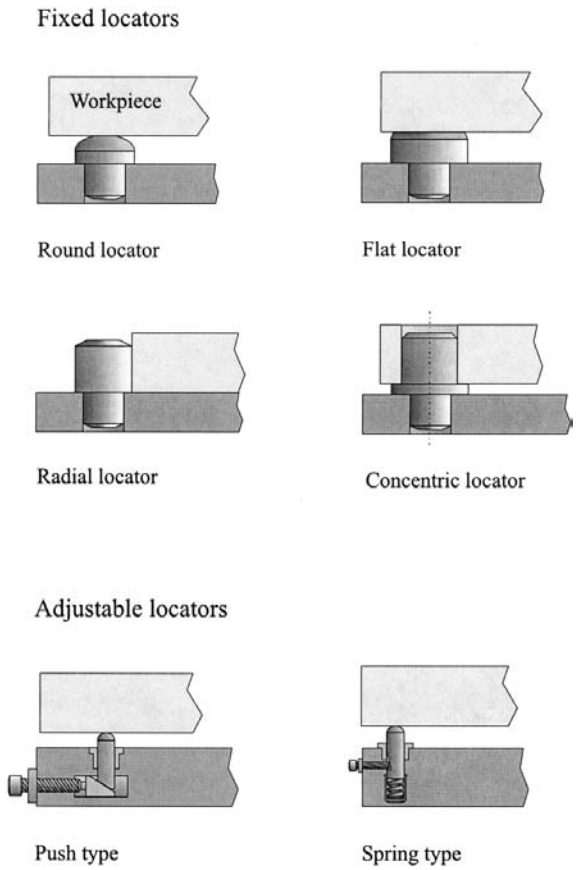

FIGURE 2 Fixed and adjustable locators.

the machine tool's table but on the workholding device's body, which is subsequently secured onto the machine tool's table.

11.1.2 Clamping

The role of a clamping device is to apply sufficient force on a workpiece to maintain its absolute immobility during the manufacturing process. Clamping forces should be sufficiently high not to allow any loosening due to potential vibrations and be directed toward support points (in the most solid sections of the workpiece) to prevent distortion or damage. Forces generated during manufacturing, however, should be counteracted by the fixed parts of the workholding device (locators and the base plate) and not by the clamps.

As with locators, clamps must allow for rapid loading/unloading of the fixture/jig and normally be located in the periphery for minimum interference with the manufacturing operations. The five basic classes of clamping are briefly described below (Fig. 3):

Strap clamps: The basic configuration comprises a bar, a heel pin, and a lever or a threaded rod. These clamps are the simplest to use and are found in most workholding devices.

Screw clamps: The moment developed by a screw is utilized to hold the workpiece in place. Although simple to use, these clamps are slower to operate than others.

Cam clamps: Cam-shaped levers are utilized in fast-operating clamping for direct or indirect application of pressure on the workpiece. Cam-action clamps would be susceptible to vibrations during the manufacturing operation.

Toggle clamps: Toggle-action clamps have the ability quickly and completely to move away from the workpiece once unlocked. The

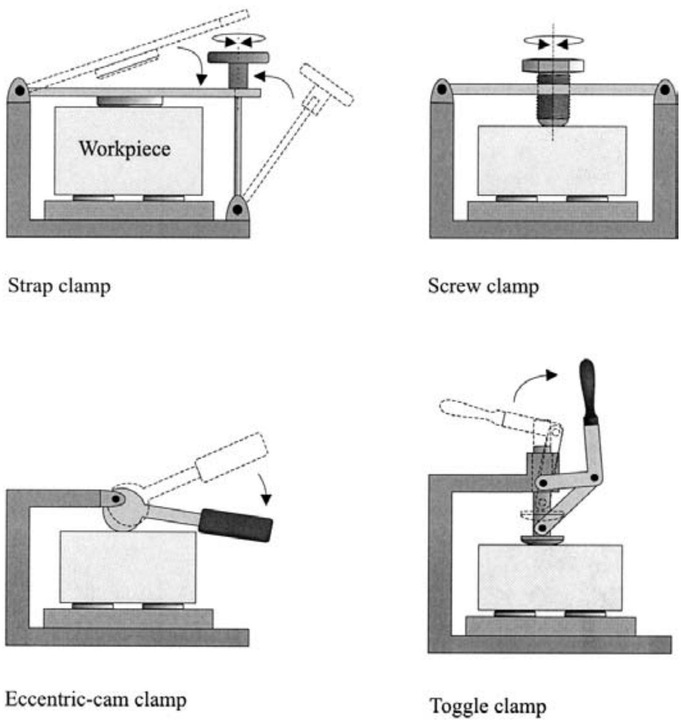

FIGURE 3 Clamps.

two common configurations used in manufacturing applications are the ones with the hold-down and straight-line-push actions.

Almost all clamping devices can be power activated using a hydraulic or electrical power source and occasionally a pneumatic power source. The obvious advantage of power activation is usefulness for automation.

Commercially available chucks (for lathes) and vises (for milling machines) are also considered as general-purpose clamping devices. Both devices can be configured for manual operation or automatic clamping. There also exist magnetic and vacuum chucks and vises for nonmechanical clamping of workpieces that would not be subjected to large forces during manufacturing.

11.1.3 Workholding Device Design

The mechanical design of a fixture/jig is a complex engineering task that includes all the typical steps of a traditional design process: synthesis, analysis, and prototyping. A tool designer can utilize the techniques addressed in Chap. 3 for effective fixture/jig design (e.g., axiomatic design theory, group technology, etc.). The outcome of this process is a specific fixture/jig configuration (layout), individual component designs, and a corresponding workpiece loading/unloading procedure.

Prior to the configuration of a suitable workholding device, however, the following issues must be addressed: the necessity of multiple fixtures/jigs owing to workpiece geometry complexity, the number of workpieces per fixture/jig, the determination of suitable surfaces on the workpiece for locating and clamping, and the sequence of workholding steps. The fixture/jig configuration process would yield the following information:

Types of locators and clamps
Positions of locators and clamps
Clamping sequence and magnitudes of clamping forces

The detailed designs (geometry, dimensions, and tolerances) of individual workholding elements are determined by workpiece geometry, contact information (point, line, or plane contact between the locators and workpiece surfaces), expected frequency of utilization (e.g., batch production versus mass manufacturing), availibility of off-the-shelf standard device geometries, mode of operation (manual versus automatic), and finally conditions of manufacturing (clean-room versus machining with coolants). Some jig and fixture design examples will be presented in the following sections.

11.2 JIGS

Jigs are workholding devices used for guiding hole-making tools into accurately located workpieces. Although used for a variety of hole-making processes, such as boring, reaming, tapping, etc., the majority of jigs are utilized for drilling. A typical jig used in drilling would include a baseplate, or a box, with a number of locators and clamps for holding the workpiece and (hardened-steel) bushings corresponding to the number of holes to be drilled.

11.2.1 Jig Configurations

Jig configurations vary from simple template: type jigs (a flat plate with a number of built-in bushings), which would be directly placed on a workpiece and held down manually during drilling, to box: type jigs that would allow drilling in different angles.

Plate Jigs

Plate jigs are variations of template-type jigs that also incorporate clamping devices for accurately and securely holding the workpiece. Leaf jigs constitute the most common configuration (Fig. 4). A workpiece is mounted onto the bottom half of the jig, located accurately, and subsequently clamped in place by the lowering of the upper half of the jig. Cam-action type latches allow for fast loading/unloading cycles.

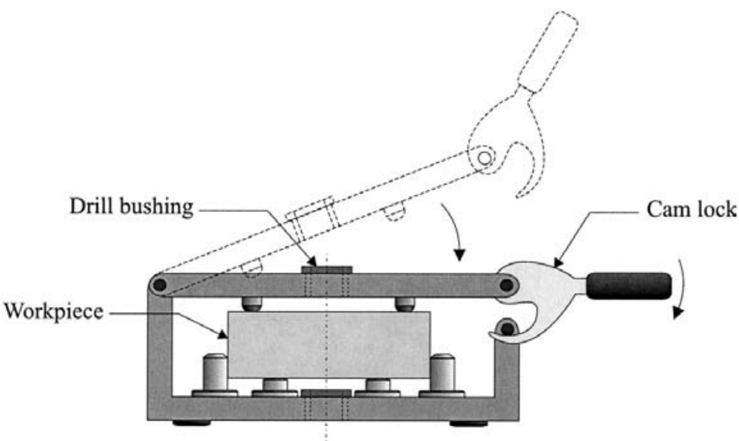

FIGURE 4 Leaf jig.

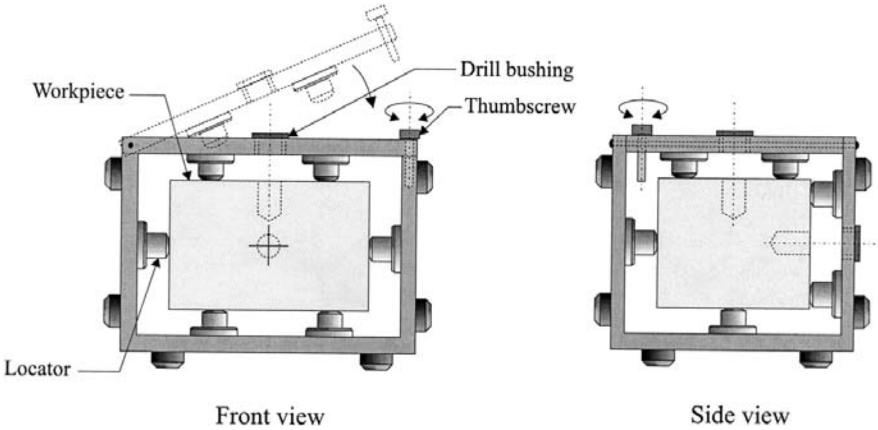

FIGURE 5 Box jig.

Box Jigs

Channel and box jigs are normally designed for complex part geometries and/or for manufacturing processes that would require drilling from a number of distinct angles, so one needs the part to be held accurately while repositioning the jig (Fig. 5). As in plate jigs, a number of locators placed on different walls of the box locate the workpiece securely while drilling is carried out. As in leaf jigs, the box is closed by a pivoting wall. Though common, placement of bushings on moving wall sections of the box jig should be avoided for better accuracy.

11.2.2 Bushings for Jigs

Drill bushings are normally manufactured from wear-resistant, hardened steel using precision finishing (grinding, or even lapping) to excellent concentricity. The most common types are press-fit, renewable, and liner bushings (Fig. 6):

Press-fit bushings are manufactured with or without "heads" and pressed directly into the jig plate for short production runs that would not require frequent changes of the bushings.

Renewable bushings slide into their respective locations in the jig plate with excellent fit and are held in place by a locking mechanism. These are typically used when multiple hole fabrication operations are performed on the same hole, which require different diameter bushings (e.g., accurate hole enlargement, tapping, etc.).

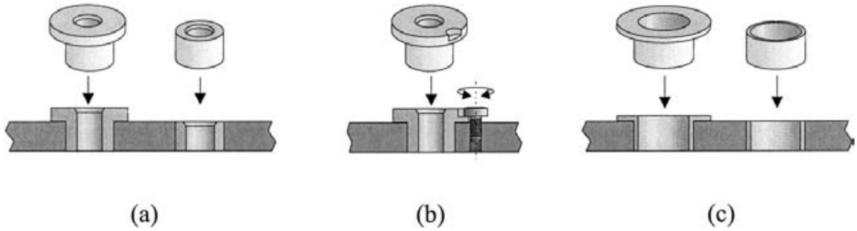

FIGURE 6 (a) Press-fit; (b) renewable; (c) liner bushings.

Liner bushings are employed for preserving the quality of the holes on the jig plate by being press-fitted into the holes and acting as "master" bushings into which the renewable bushings are fitted in turn. That is, they provide renewable bushings with high-accuracy, hardened holes to be fitted into.

11.3 FIXTURES

Fixtures are workholding devices utilized for locating, supporting, and clamping workpieces for fabrication and assembly tasks. Traditionally, they do not include special components, such as bushings, in order to guide tools. They do, however, employ components, such as tenons, for referencing purposes. Fixtures have been classified according to their configuration and/or according to the manufacturing task for which they are employed. In most cases, they are built to withstand external forces greater than those experienced by jigs, and to provide high positioning accuracy.

In this section, we will first briefly review dedicated fixture configurations that are typically used by most manufacturing applications, while discussing some applications' needs in more detail, and then discuss fixture modularity and reconfigurability, a topic of importance to flexible manufacturing.

11.3.1 Fixture Configurations

The majority of fixtures in use today are called dedicated workholding devices, since their configuration is fixed for one workpiece geometry, in contrast to modular fixtures, which can be assembled and disassembled according to the task at hand. Both dedicated and modular fixtures are normally built on a support plate using a variety of locators, supports, and clamping devices (Fig. 7). Occasionally, plates may be configured to provide an orthogonal wall of support (with respect to the machine table)

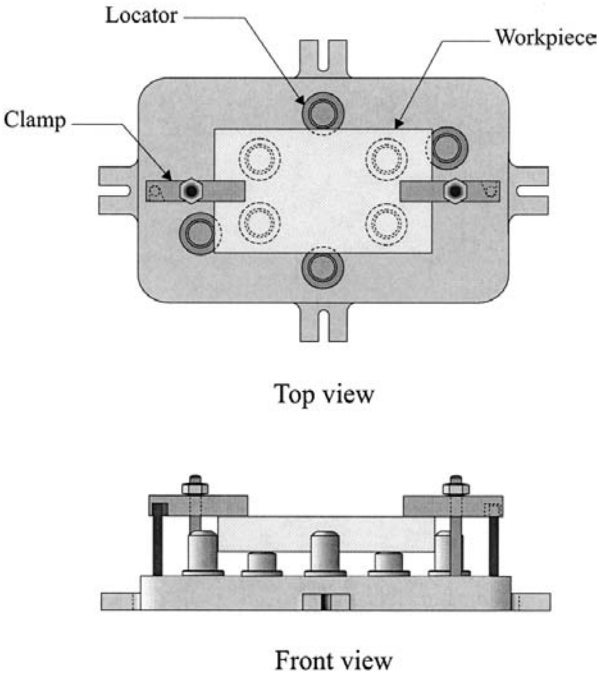

FIGURE 7 Plate fixture.

or even an arbitrary inclined wall of support ($< 90°$). In all cases, however, the fixture plate is constructed with special cut out slots for efficient mounting onto the worktables of manufacturing machines. Once mounted and secured via multiple bolts, they provide high rigidity. Tenons (square blocks) positioned underneath the plates fit into the narrow segments of the (reverse) T-slots of the worktables for improved accuracy in positioning.

Vise-held fixtures are small plate fixtures that are manually mounted onto the worktables of machines and fixed in place through the use of vises or chucks. They are normally targeted for light machining (low cutting forces).

Milling Fixtures

Milling is an intermittent cutting process, in which the (periodic) cutting forces can be very high (Chap. 8). The locators and supports of the fixture must be designed for these forces and configured to resist them while maintaining workpiece location accuracy and not allowing deflections. Tenons should be used to locate the fixture with respect to the worktable, and reference-setting blocks should be used to locate the fixture with respect to the cutting tool. Sufficient clearances must be incorporated for effective removal of chips and drainage of coolant liquid.

Turning Fixtures

The turning operation on a lathe subjects the workpiece, and thus the fixture holding it, to centrifugal forces in addition to the (continuous) cutting forces. Although the majority of workpieces can be directly mounted onto the (3- or 4-jawed) chuck of the lathe, those workpieces that cannot must be held by well-balanced fixtures, which may be in turn held in place by the chuck of the lathe or directly fastened onto the faceplace of the lathe (Fig. 8). An unbalanced fixture/workpiece assembly will cause vibrations, thus leading to cutting-tool chatter (Chap. 8). Balance can be achieved, when necessary, by the addition of nonfunctional weights to the fixture.

Assembly Fixtures

The primary objective of an assembly fixture is accurately to locate and clamp two parts prior to their joining operation (e.g., riveting, welding, etc., Chap. 10). Though rarely subjected to large fabrication forces, the clamping devices must provide sufficient reinforcement (especially in welding operations) while allowing fast loading/unloading cycles. Welding fixture designers should also consider the following workholding issues: protection of fixture components from sputters and heat; ensuring conduction of electricity and good grounding; proper heat dissipation control; and the use of

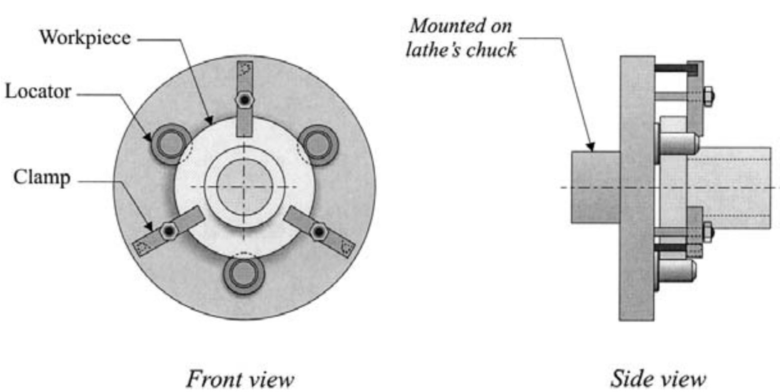

FIGURE 8 A turning fixture.

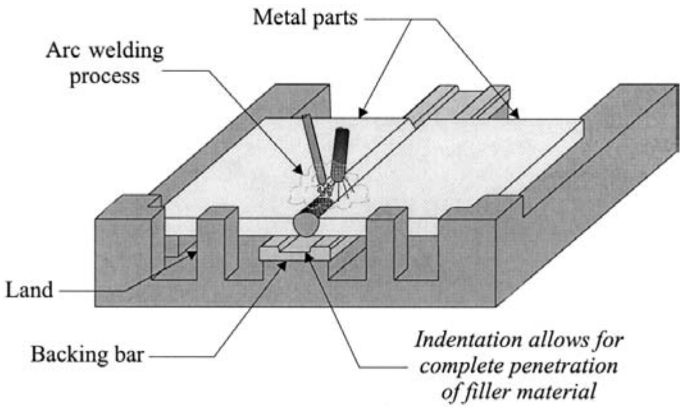

FIGURE 9 A welding fixture.

suitable backing bars (placed under the joints for arc welding) for complete penetration of filler material (Fig. 9).

11.3.2 Flexible Fixtures

Operational flexibility in manufacturing requires the use of flexible workholding devices that can be reconfigured for the latest workpiece at hand. Although the beginnings of such reconfigurable fixtures can be traced back to there early 1940s in Europe, in the form of modular devices, innovative fixture designs suitable for programmable automation have only been developed since the late 1970s and primarily by academics. However, despite a large number of such reconfigurable/programmable fixture design proposals, the manufacturing industry mostly still continues to use fully dedicated fixture configurations with only sparse efforts to use modular fixtures and very rarely any programmable devices.

Modular Fixtures

The rationale of using modular workholding devices is cost reduction by being able to accommodate multiple parts on a reconfigurable fixture, thus minimizing design and fabrication efforts for the fixture. Modular fixtures comprise a set of standard components (with variable dimensions), such as locators, V-blocks, clamps, and supports, which can be assembled on a base plate (with T-slots or holes) (Fig. 10). The assembly of the fixture can be carried out around an actual (reference) workpiece or using accurate measurement devices according to a plan, normally generated on a CAD workstation.

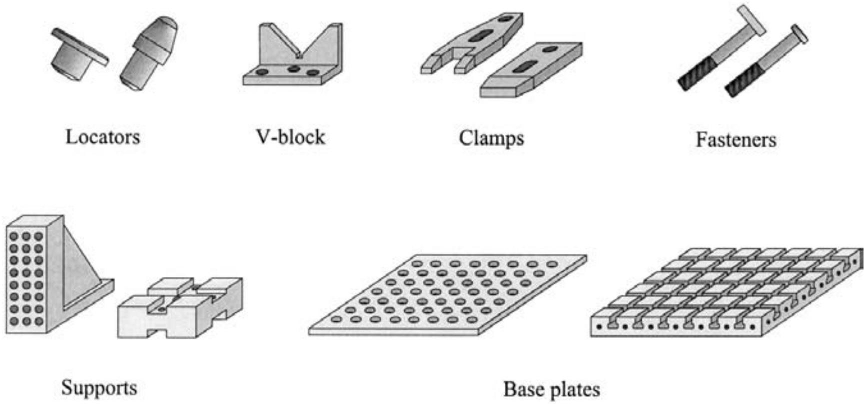

FIGURE 10 Modular fixture components.

As discussed above, modular fixtures can be utilized in flexible-manufacturing (or job-shop) environments for one-of-a-kind or small-batch productions. A typical application is the manufacturing (of the components) of machine tools themselves. Prototype production and pattern fabrication for casting are other common applications.

Modular fixtures are normally classified according to the geometry of their base plate: T-slot versus hole (or dowel-pin)-based systems (Fig. 11). The former systems were the first modular fixture configurations developed in order to duplicate the advantages of T-slot-based worktables on milling machines. Their primary advantage is the continuous variability/reconfigurability of individual components along the full range of the slots. However, all fixture components must be accurately placed on the plate and fastened down securely to counteract the cutting forces. Hole-based modular fixtures, on the other hand, can be easily reconfigured based on a CAD plan, and they provide higher stiffness. Furthermore, hole-based plates are easier to fabricate, though they provide a more limited reconfigurability owing to the discrete placement of the holes. Finally, one can note that there are hybrid plates that include holes and T-slots.

An important issue in modular fixtures is the size of the inventory of components. In order to accommodate workpieces of various sizes and shapes, the heights, widths, diameters, etc. of locators, supports, and clamps must also be variable. In most commercial modular fixture systems this variability is achieved by using add-on blocks for height variability and employment of a large number of locators and V-blocks of different sizes. The academic literature includes, however, designs of modular components whose dimensions can be continuously adjusted.

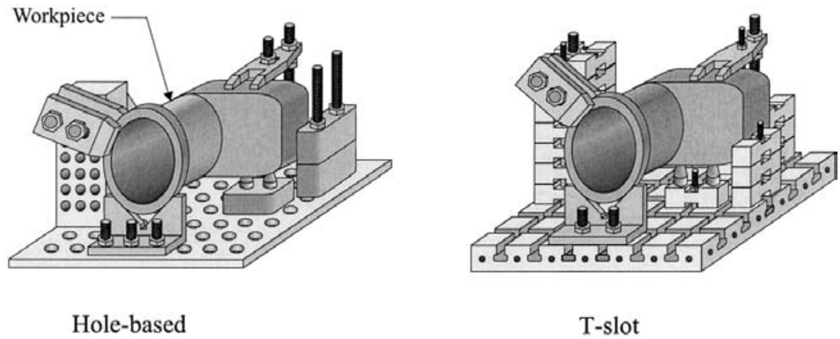

FIGURE 11 T-slot and hole-based modular fixtures.

Reconfigurable/Programmable Fixtures

The term reconfigurable fixtures has often been used interchangeably with modular fixtures that have limited ability to reconfigure. In this section, the former term is reserved for workholding devices whose locators, supports, and clamps can be adjusted in the continuous domain (versus in discrete increments) to adapt to the geometry of the workpiece.

The most commonly known reconfigurable fixture is the conformable clamping system developed by Cutkosky et al. for machining turbine-blade forgings (Fig. 12). The two primary characteristics of this system are (1) the use of variable-height (pneumatic) locators that fit the underneath profile of the turbine blade along a line, and (2) the use of a flexible belt that wraps around the upper profile of the turbine blade. The accurate positioning of the line of support and the exact height determination of each one of the

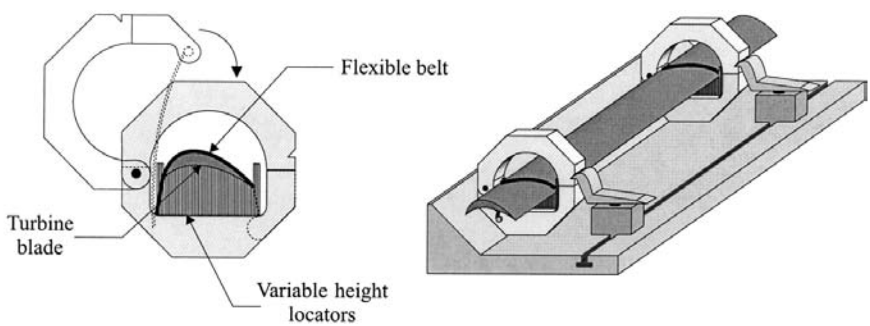

FIGURE 12 Conformable clamping system.

locators must be carried out with great care. The use of a master template has been proposed for this purpose.

An extension of the conformable clamping system from a 2-D line support to a 3-D surface support could be achieved via a ‘‘bed of nails,’’ which would provide support to thick- and thin-walled surfaces. Such custom-made fixtures have been used in the aerospace industry for the drilling of thin-walled, large fuselage parts. Naturally, one may plan to use only a partial set of ‘‘nails’’ (locators) that would provide sufficient rigidity. The optimal number and locations of these locators can be determined using finite-element-based stress analysis tools.

An important issue to consider in workholding for flexible manufacturing is the intelligence of the fixtures. In this context, there have been only

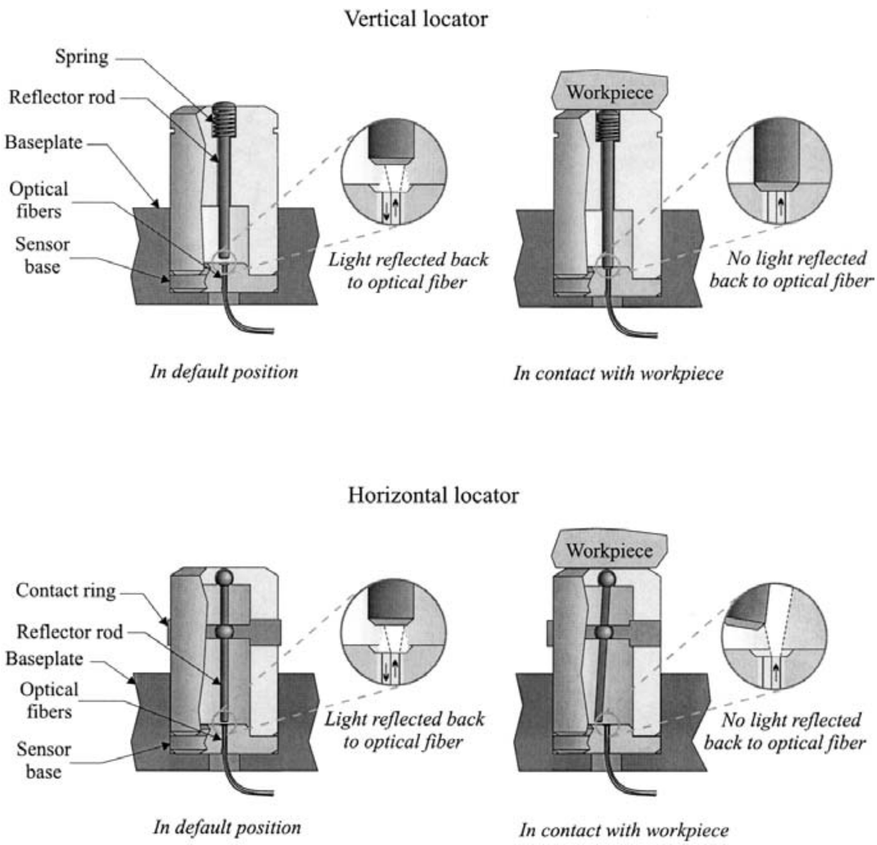

FIGURE 13 Intelligent locators for programmable fixtures.

a limited number of attempts to incorporate sensors into workholding devices in order to receive real-time feedback on the status of the fixturing process. Two challenges in programmable (intelligent) fixture development are (1) the detection of the accurate assembly of the reconfigurable fixture components on the baseplate and (2) the subsequent detection of the workpiece placement on the fixture and its clamping. Both of these challenges must be addressed without negatively affecting the accuracy of locating and clamping the workpiece. A variety of such fixture components were developed at the University of Toronto for a hole-based plate modular fixturing system (Fig. 13). This fixture is able to detect the presence of objects placed on it and activate clamps automatically for autonomous, computer-based workholding.

11.4 COMPUTER-AIDED FIXTURE DESIGN AND RECONFIGURATION

Fixture design for manufacturing may be a complex endeavor owing to accuracy needs in an environment of nontrivial tool paths and, where applicable, cutting forces. Commonly this task is carried out by an experienced and skilled tool designer. Given a workpiece geometry and manufacturing conditions, the designer is required to develop the most suitable fixture (dedicated or modular) and preferably a process plan for its fabrication. As in any product design, the tool designer should utilize existing design methodologies (Chaps. 3 and 4) and computer-aided-engineering (CAE) analysis tools (Chap. 5) in the design and reconfiguration of fixtures/jigs.

The role of computer-aided design (CAD) varies according to the fabrication strategy: for mass production, where dedicated fixtures would be utilized for long periods of time, the emphasis would be on design, whereas for small batch sizes or one-of-a-kind production, the emphasis would be on the reconfiguration of the modular workholding setup. In both cases, however, finite element analysis must be utilized for the prevention of potential workpiece deflections due to fabrication forces.

11.4.1 Design of Fixtures/Jigs

The most basic approach to fixture design is the utilization of a CAD package by a skilled tool designer for a design from scratch. The designer builds the fixture around the CAD model of the workpiece using a graphical user interface based on his or her past experience and knowledge of expected fabrication conditions. Some commercial software packages provide designers with a set of premodeled fixture components that they can retrieve from the database and modify them as necessary.

Group technology (GT) principles (Chap. 3) can be effectively utilized in the fixturing of workpieces with geometric similarity. The objective is to access fixture designs used in the past for workpieces that are similar to the workpiece at hand. The retrieval of the most appropriate/useful (past) fixture design can be achieved by the following sequential approach in a CAD environment, where all workpiece geometric models have been classified and coded:

1. Determine the GT code for the workpiece to be fixtured using the company's available classification and coding system.
2. Search the database of workpieces, for which there exist corresponding fixtures/jigs, to determine the most similar (past) workpiece geometry based on the GT code determined in Step 1.
3. Retrieve from the fixture database the (fixture) design corresponding to the (past) workpiece identified in Step 2.
4. Evaluate whether the most similar past fixture design could be effectively modified to yield a new design for the workpiece at hand. If the answer is no, then, we must return to Step 2 in order to determine and evaluate other similar designs, though the probability of finding a better past fixture design would be low, if the coding and classification system has functioned properly in the first iteration. After several evaluation iterations, Steps 2 to 4, if a suitable past fixture design can still not be identified, the designer must design a new fixture from scratch.If a retrieved fixture design is deemed to be suitable, the process continues.
5. Access all past information stored in the database regarding the past fixture design: reasoning behind the selection of specific locators/supports/clamps, etc., as well as the evaluation metrics for the specific fixture configuration chosen.
6. Modify the (retrieved) fixture design for the workpiece geometry and fabrication conditions at hand. This step is an iterative process itself, where different designs and configurations must be analyzed using CAE analysis tools (Sec. 4.2 below).
7. Store the new workpiece and fixture models and other pertinent data in their appropriate databases according to the GT code (of the new workpiece) for future use.

The above sequential process can be utilized for the design of dedicated fixtures as well as for the reconfiguration of modular fixtures.

There have been several attempts by academic investigators to develop CAD-based tools for the automatic synthesis of fixture designs (with almost no manual intervention). These systems utilize a variety of reasoning techniques (including heuristics and analytical models) to determine locating and clamping points on the workpiece, choose corresponding fixture component geometries, and assemble the fixture (in the CAD's virtual environment) for subsequent interference checks. Generative fixture design is another term used for such experimental design procedures.

11.4.2 Fixture Configuration and Analysis

Fixture configuration is commonly referred to as the process of determining the positions of locators and clamps for modular fixtures. However, as discussed earlier in this section, one must also select these positions with great care in the case of dedicated (nonreconfigurable) fixtures. The objective is engineering analysis for optimal fixture configuration.

Due to time-varying forces acting on the fixture, the problem at hand is a dynamic type, where fixture and workpiece behavior under loading must be analyzed. The analysis is almost always carried out using (numerical) finite element–based modeling owing to the complexity of workpiece geometry. The optimization process attempts to vary the fixture configuration in order to minimize deflections with preferred minimal clamping forces. Fixture configuration includes the following (optimization) variables: the number, types, and positions of locators, supports, and clamps and clamping forces. The problem is a mixed integer/continuous-variable type and must be solved by employing an appropriate search method (Chap. 5).

REVIEW QUESTIONS

1. Define workholding (fixturing) and state its primary objectives.
2. Define jigs versus fixtures.
3. Explain the 3-2-1 principle in workholding.
4. Why should locators be manufactured as entities separate from the body of the fixture/jig?
5. Define locating versus clamping. Why should manufacturing forces be directed toward support points and not be compensated by clamps (i.e., directed toward clamps)?
6. Why should clamps be power activated (versus being manual)?
7. Is the design process of a fixture different from that of the part it is manufactured to fixture? Explain.
8. Discuss the different classes of bushings available for jigs.
9. Discuss the use of tenons in the placement of fixtures onto machine worktables.
10. Compare the principal requirements for machining fixtures versus those for assembly fixtures.
11. Discuss the need for flexible fixtures in small-batch and/or one-of-a-kind manufacturing environments.

12. Compare modular fixtures versus reconfigurable/reprogrammable fixtures.
13. Compare the use of hole-based base plates versus T-slot-based ones in modular fixturing.
14. Why should fixtures/jigs be reprogrammable?
15. Discuss the use of computer-aided design (CAD) and engineering analysis (CAE) tools in fixture design. In your discussion, also refer to issues such as, group technology (GT), generative design, and so on.

DISCUSSION QUESTIONS

1. Discuss possible sensing technologies that can be incorporated into different workholding devices for the on-line monitoring and control of the manufacturing process, while the parts are being fabricated/assembled.
2. Fixtures can be designed for a specific range of metrics within the targeted family of products: (1) Those that allow reconfiguration via continuous and/or discrete incremental changes, or even through modularity of certain subcomponents, or (2) those that have been already manufactured in different dimensions, etc., for different product dimensions. Discuss these modes of fixture design in terms of manufacturing difficulties, durability, safety, cost, etc.
3. The use of design features has long been considered as improving the overall synthesis and analysis stages of products owing to the potential of encapsulating additional nongeometric data, such as process plans, in the definition of such features. Discuss feature-based design, in which the user, through some recognition/extraction process, can access and retrieve individual similar or identical features on earlier product/fixture designs and utilize them for the design of the fixture at hand.
4. Finite-element modeling and analysis (FEM/A) methods have been developed to cope with the engineering analysis of complex product geometries and/or physical phenomena. Discuss the use of FEA during the (iterative) fixture design process (i.e., synthesis analysis) for the determination of optimal design parameter values, for example in verifying part deflections under clamping and/or manufacturing forces.
5. Fixturing is a typical design process that involves the iterative synthesis and analysis stages, during which we would determine the optimal support and clamping positions for a workpiece at hand and accordingly configure, design and manufacture a mechanical fixture. Due to high accuracy requirements, the cost of a complex fixture can also be very high. This cost is normally amortized over a large number of identical parts in mass production cases. Discuss the utilization of

modular fixtures for small-batch and one-of-a-kind manufacturing cases. Address issues such as accuracy of components, ease of assembly, computer-aided planning of fixture configuration, and others.

6. Would several different GT based classification and coding systems be needed in a company for different objectives? That is, one system for product/fixture design, one system for manufacturing planning, and yet another for cost engineering.
7. In the near future, although the majority of engineering products will be modeled in the virtual (computer) space, representing the starting point of the design and manufacturing process, some products will still be crafted manually by artisans and/or industrial designers. Discuss the computer-aided design and manufacturing of fixtures for such products, whose features are not originally defined by exact mathematical relationships.
8. Machining centers increase the automation/flexibility levels of machine tools by allowing the automatic change of cutting tools via turrets or tool magazines. Some machining centers also allow the off-line fixturing of workpieces onto standard pallets, which would minimize the on-line setup time (i.e., reduce downtime of the machine): that is, while the machine is working on one part fixtured on Pallet 1, the next part can be fixtured on Pallet 2 and loaded onto the machine when it is has completed operating on the first part. Discuss the use of such universal machining centers versus the use of single-tool, single-pallet, unipurpose machine tools.
9. Job shops that produce one-of-a-kind products have been considered the most difficult environments to automate, where a product can be manufactured within a few minutes or may require several days of fabrication. Discuss the role of reconfigurable fixtures in facilitating the transformation of such manual, skilled-labor dependent environments to intensive automation-based environments.
10. Manufacturing flexibility can be achieved at three levels: operational flexibility, tactical flexibility, and strategic flexibility. Discuss operational flexibility. Is fixturing automation a necessary or a desirable tool in achieving this level of flexibility?

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