Computer-Aided Manufacturing

Second Edition

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conventional milling is more pronounced in materials with high ductility and work-hardening capability. Milling is an interrupted operation that usually demands higher tool toughness, honed edge, or negative land on the rake face. Another machining operation, drilling, is a process in which a fixed-diameter cutting tool is fed into a workpiece. The nominal size of the hole is the same as the nominal size of the tool. Drilling can be performed on a lathe, milling machine, or a drilling machine. Drilling and turning operations are illustrated in Figure 5.7.

5.5 WORKPIECE HOLDING PRINCIPLES

Fixtures are used to locate and constrain a workpiece in machining and other manufacturing operations. To ensure that the workpiece is produced according to the specified shape, dimensions, and tolerances, it is essential that it is appropriately located and clamped on the machine tool. The configuration of a machining fixture depends not only on workpiece characteristics, but also on the sequence of machining operations, magnitude and orientation of the expected cutting forces, capabilities of the machine tool, and cost considerations. A fixture could be specially designed and fabricated for each workpiece (dedicated fixtures), or a fixture could be constructed from standardized fixturing elements chosen from a catalog (modular fixtures). Usually, it is expensive to design and build a fixture for each individual type of workpiece, so it is often considered satisfactory to select readily available fixturing elements from a catalog. Each fixturing element has a specific function, and a number of elements can be combined to build a complete fixture.

The traditional approach to designing fixtures for prismatic parts has been for the human designer to look at the workpiece drawing and to analyze the geometrical features from the viewpoint of obtaining the desired orientation and restricting the necessary degrees of freedom. A fixture designed from these initial considerations is further modified to conform to the machining sequence and to the configuration of the machine tool on which the part is manufactured. Other external issues, such as the mechanism for loading and unloading the workpiece (human/robot), setup times, chip disposal, and so on, will also influence the fixture design process. The ability to come up with a feasible solution will depend on the designer's experience, the designer's ability to recall fixture designs for similar workpieces, his or her knowledge of material-removal operations, and the workpiece's material properties. Obtaining a suitable design in this manner can be called *nonalgorithmic,* because it involves trial and error.

5.5.1 Fixtures and Jigs

General principles in the practice of fixture design are more or less agreed upon; however, a systematic structured design procedure does not exist. The relationship among the chosen locating and clamping scheme and the machining sequence, process parameters, and workpiece characteristics has not been adequately analyzed. A unified treatment of these issues is the key to building fixtures. A survey of common principles in workholding and terminologies will be presented.

In general, a workholding device serves three primary functions: location, clamping, and support. The workpiece has to be correctly positioned, with respect to the tool, in order to maintain the specified tolerances: *location*. This position of the workpiece must be maintained while it is being subjected to cutting forces: *clamping*. Finally, the deflection of the workpiece, due to the tool and the clamping forces, must be minimized: *support*. Total workpiece control involves both linear equilibrium (balance of forces) and rotational equilibrium (balance of moments). Correct placement of locators, supports, and clamps enables this equilibrium to be achieved. In addition to the three primary functions, fixtures may also perform the operations of centralizing and guiding. Where appropriate, as found in specialized fixtures called jigs, a special guiding system leads the tool to its precise position relative to the work. An abstract description of the individual functions of a fixture is shown in Figure 5.9. To guarantee the exact relationship between the tool and the work, four important relationships or "couplings" must be controlled (Weck and Bibring, 1984). As shown in Figure 5.10, these are the relationships among: (1) tool and tool holder, (2) tool holder and machine, (3) workpiece and clamp, and (4) clamp and machine. Among other criteria, certain practical considerations that indicate a good design are as follows:

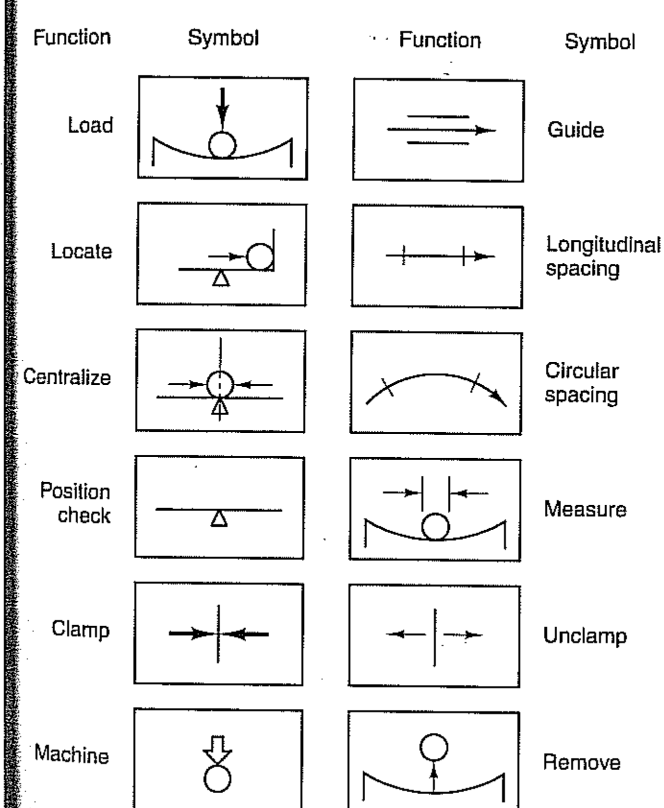

Figure 5.9 Functions of fixtures and their symbolic representation (Weck and Bibring, 1984).

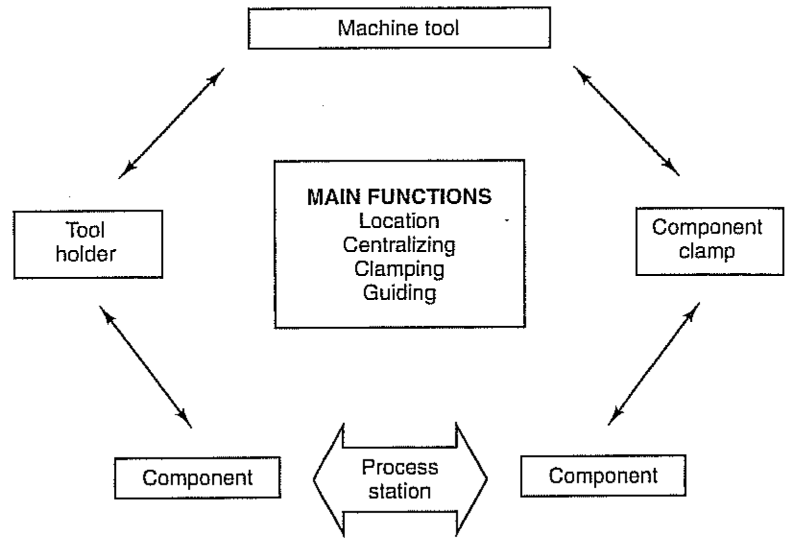

Figure 5.10 Four key fixturing relationships (Weck and Bibring, 1984).

1. Locating and clamping methods should reduce idle time of the machine tool to a minimum.
2. The configuration of the locators and clamps should not interfere with the swept volume of the cutter. Collision avoidance between the cutting tool and fixturing elements is imperative for the safety of the operator, and to prevent damage to the machine tool or cutter.
3. Adequate clearance, in the form of channel ways, should be provided to allow for good chip clearance. This implies that awkward corners, wherein chips tend to collect, should be avoided. Similar considerations dictate the ease with which coolants will be able to access the cutting edges.
4. The design should be robust in order to withstand intermittent cutting and avoid vibration effects.
5. The design should be foolproof, that is, within reason, it should be impossible to insert the workpiece incorrectly in the fixture.

Table 5.4 summarizes the general considerations in fixture design.

5.5.2 Location

Location establishes a desired relationship between the workpiece and the fixture, which in turn establishes the relationship between the workpiece and the cutting tool. Weck and Bibring (1984) define "locating" as using faces of the component as reference planes. A free body in space has six degrees of freedom, that is, a linear and rotational motion for each of the X, Y, and Z axes. These 6 basic motions can occur in 2 directions

TABLE 5.4 FIXTURE DESIGN CONSIDERATIONS

1. Locating considerations	
(a) Radial	(b) Concentric
(c) From surfaces	(d) From points
(e) Other	
2. Positioning considerations (relation to tool and orientation in the fixture)	
(a) Indexing (linear and circular)	(b) Rotating
(c) Sliding	(d) Tilting
3. Clamping considerations	
(a) Rapidity	(b) Amount of clamping forces
(c) Direction of clamping forces	(d) Actuation (manual, power)
4. Supporting considerations	
(a) Relation to tool forces	(b) Relation to clamping pressure
(c) Relation to thin-walled sections of workpiece	
5. Loading considerations (including manual lifting and sliding; hoisting; unloading chutes, magazines)	
(a) Rapidity	(b) Ease
(c) Safety	
6. Coolant considerations	
(a) Direction	
7. Chip considerations	
(a) Accumulation	(b) Disposal

Source: Wilson and Holt (1962).

each for a total of 12 degrees of motion are possible. Usually, locators will eliminate as many degrees of freedom as are possible while still being able to perform the operation with the required accuracy. The most common method of location is 3–2–1, or the six-points principle. The first plane, which usually has the largest surface area, establishes the primary locating plane (3-plane), and is located by three points [Figure 5.11(a)]. The

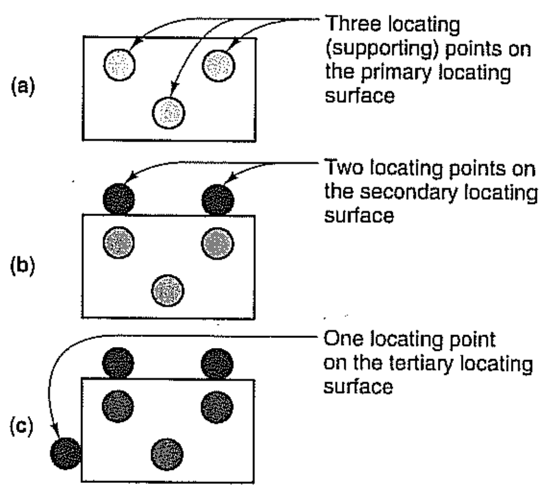

Figure 5.11 3–2–1 location: (a) 3-Plane, (b) 2-Plane, and (c) 1-Plane (Hoffman, 1987).

surface with the next largest amount of area generally establishes the secondary locating plane (2-plane) and is located with two locators [Figure 5.11(b)]. The final locator is placed on the tertiary plane (1-plane), to complete the location of the part [Figure 5.11(c)]. The 3-plane restricts two rotational motions and one linear motion, the 2-plane restricts one rotational and one linear motion, and the 1-plane restricts one linear motion.

The type of location is governed by the type of feature and the number of faces being machined. Locating arrangements for different production requirements are shown in Figure 5.12. To machine one face, control of dimension a is required, and hence, only one locating plane is necessary. Two locating planes are required for machining an open slot, as dimensions a and b need to be controlled. Full location (three planes) is necessary for milling a blind slot, as dimensions a, b, and c need to be controlled. The 3–2–1 principle is ideal for prismatic or rectangularly shaped workpieces

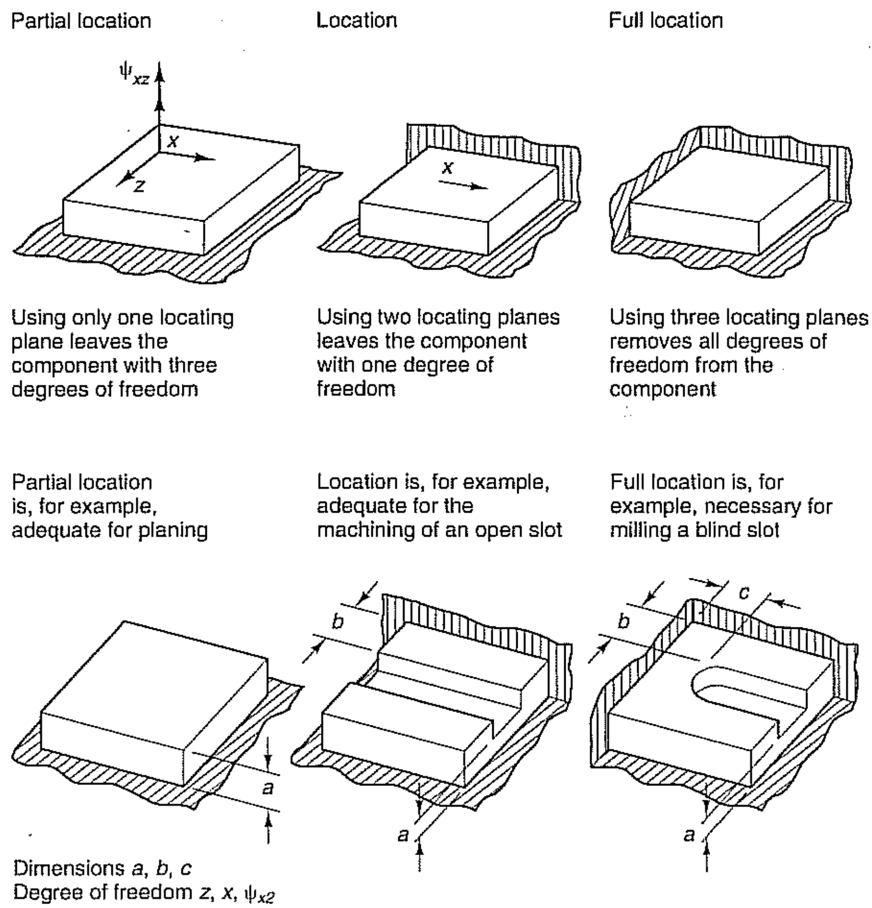

Figure 5.12 Degrees of freedom and number of locating planes for differing production requirements (Darvishi and Gill, 1988).

only. For simple cylindrical or conical shapes, just five locators are needed, because one rotation is stopped purely by friction (Figure 5.13).

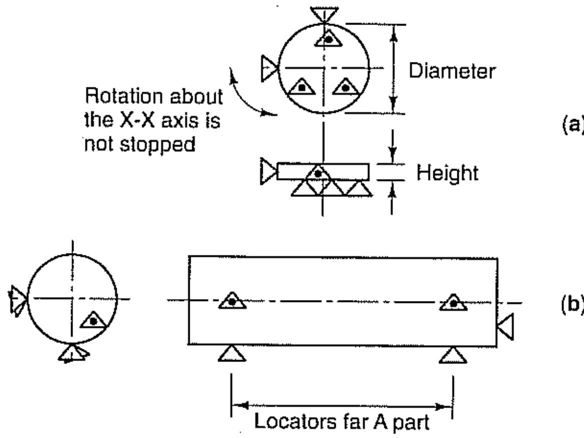

Figure 5.13 Workpiece control (Eary and Johnson, 1962); (a) short cylinder, (b) long cylinder.

By the act of location, a machinist establishes a relationship between the features of the workpiece that are being machined in the given setup, and other features being used as a reference, in order to locate the workpiece at the desired position in the machine-tool coordinate system. To determine the reference features or surfaces of the workpiece, it is vital to examine how the workpiece dimensions are specified on the blueprint. Incorrect placement of locators will cause the workpiece to go out of tolerance. It is important to (1) select the correct surfaces for placement of the locators, and (2) position the locators correctly on the surface selected.

Excess of locators exist when more than six locators are provided for a prismatic workpiece in a single fixture. Four points of location, all on one surface, allow a workpiece to be clamped on slightly different planes, which may be enough to throw the workpiece out of tolerance. A locator directly opposite another locator is also harmful, because the distance between the two locators may not be large enough to allow for size variation of the workpiece.

Location may involve centering. Whereas locating normally brings one surface of the workpiece into proper position relative to the fixture, centering is applied to two surfaces. It usually locates a plane or an axis within the part. A centralizer is a combination of fixed and movable locators that provide positive contact and pressure without clearance. Typical combinations of locators and centralizers are shown in Figure 5.14. Double centering is accomplished whenever an axis is located. Locating requirements are achieved by providing plane location, concentric location, or radial location (Figure 5.15). In general, the following principles in location are commonly applicable:

1. Stability of the workpiece is best when the locators have the largest overall distance between them. This also diminishes the effect of surface irregularities, dirt,

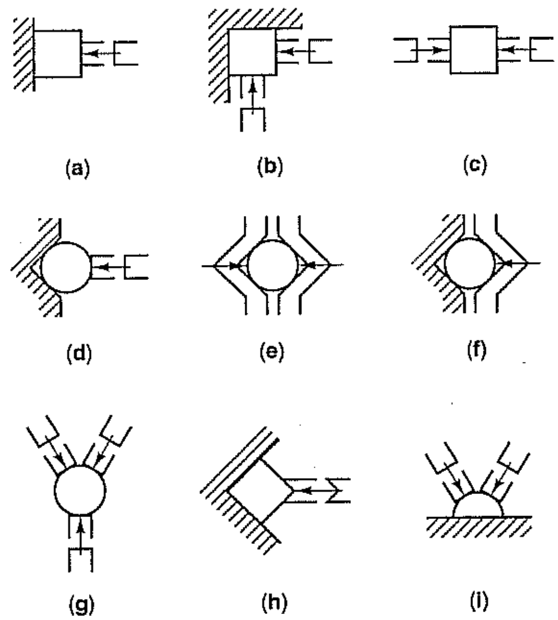

Figure 5.14 Centering operations: (a) single defined, not centered; (b) double defined, not centered; (c) single centered; (d) single centered; (e) double centered; (f) single centered; (g) double centered; (h) single centered; (i) single centered. (Henriksen, 1973).

and locator wear, on the position of the workpiece. However, locator spacing cannot be unduly large, in order to minimize workpiece deflection.

2. The center of gravity of the workpiece should be as low as possible and close to the centroid of the three locators in the 3–2–1 system.
3. Good dimensional control is achieved when locators are placed on one of the two surfaces, to which the dimension is shown, on the part drawing. When the drawing specifies close tolerances on parallelism, perpendicularity, or concentricity, more than one locator must be placed on one of the two surfaces to which the tolerance applies (Eary and Johnson, 1962).
4. Locating surfaces should not be larger than is necessary for proper support and wear. It is hard to keep larger surfaces clean and free of chips, which could cause inaccuracies. If possible, the locating surfaces should be completely covered by the workpiece, so that chips cannot fall on the locating points.

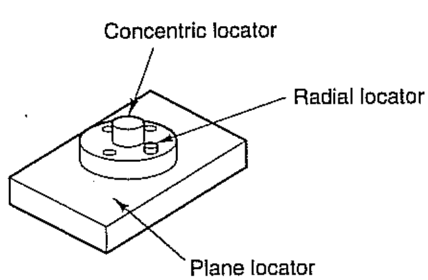

Figure 5.15 Three locating methods (Hoffman, 1987).

5. Ideally, locating surfaces should be fixed. Movable surfaces should be used for clamping only.
6. Buttons and pins—rather than flat surfaces—are preferable for locating, as they are easier to keep clean and afford easier adjustment for wear. Locating pins from previously drilled holes should be hardened and ground and have sufficient clearance for chips and burrs. These pins should locate from only one diameter, when used with counterbored holes.
7. Foolproofing the locating arrangement is desired, so that it is not possible to place the part in an improper position (Hamner, 1982).

5.5.3 Supporting and Clamping

Once positioning of the workpiece is accomplished by the locating arrangement, further control of the workpiece is necessary. The function of any clamping device is to apply and maintain a sufficient counteracting holding force to a workpiece while it is being machined. The workpiece may deflect, within elastic limit, due to the cutting forces, clamping forces, or its own weight. Excessive clamping and cutting forces may also cause distortion of the workpiece, that is, deflection beyond the elastic limit. As defined by Eary and Johnson (1962), a support is a device to limit or stop the deflection of a workpiece. Supports are either fixed, adjustable, or equalizing. The fixed support is placed away from the locating plane, against the locators, so that the workpiece will not contact the support.

Under the influence of cutting forces, the workpiece is permitted to deflect and contact the fixed support, thus limiting deflection. An adjustable support is suitable for uneven surfaces typical for castings. This type of support is kept away from the workpiece during location but adjusted to contact the workpiece after it has been clamped. Equalizing supports are connected units in which the depression of one point causes the other points to rise and maintain contact.

The clamping arrangement must force the workpiece to make contact with all locators, if not already so. Clamps must also maintain the workpiece contact at all locators, in spite of cutting-force variations, inertia forces, dead weight, and vibrations in the MFTW (machine–fixture–tool–workpiece) system. To ensure correct clamping of the workpiece, the following points may be considered.

1. The design must permit the clamps to act against the locators, so as to minimize the deflection due to clamping forces. For geometries where clamping forces cannot be applied opposite the locators, supports may be used to control the deflection caused by clamping forces. A recent method of clamping the workpiece is SAFE (self-adapting fixture element), which uses flat contact areas of hardened steel balls that are free to swivel within their sockets (Smith, 1982; Drake, 1984; Kuznetsov, 1986a). The balls automatically accommodate irregularities in the workpiece surface and provide contoured support without causing distortion.
2. The clamping scheme should be such that maximum cutting forces are directed toward the solid part of the fixture body and not toward the clamp.

3. Cutting forces should be absorbed by a fixed locator/support and not by friction between the work and the clamp.
4. Workpiece surface quality may dictate placing the clamps on noncritical surfaces.

Power clamping, which uses hydraulic or air/hydraulic-actuated components to provide the clamping force, is widely used ("Fast Clamping," 1975). A number of U.S. companies provide off-the-shelf components for power clamping systems (Carr Lane, 1988; De-Sta-Co, 1988; Owatonna Tool Co., 1988; Vektek, 1988). For a description of the various clamp designs used for NC machines, refer to Kuznetsov (1975).

5.6 PART SETUP OR ORIENTATION

The features of a workpiece are machined in a certain sequence, as given in its process plan. These features (pockets, slots, holes, and so on) are located on different sides (faces) of the workpiece. Usually, all the features cannot be accessed (machined) while the workpiece is in a given orientation. An *orientation,* or *setup,* refers to a unique locating, supporting and clamping configuration. Every machining operation has a fixturing configuration that is best for the operation but may not be a practical solution. One would like to find a subset of such feasible fixturing configurations whereby all the operations can be performed within those configurations. Therefore, it is necessary that the machining operations be grouped into setups. Grouping depends on the geometry of the individual features and availability of cutting tools. Each setup will have a so-called primary positioning face, usually the 3-plane, on which the workpiece rests, and also the remaining positioning planes (2-plane and 1-plane). In addition, a setup will also have a unique clamping scheme. Thus, each orientation requires a separate fixture. Because changing from one setup to another involves unclamping/removing the workpiece from one fixture and locating/clamping it into another fixture, the number of setups (fixtures) should be minimized to get the best accuracy.

The face of the workpiece, used as reference for any machining operation in a given setup, may be called the *machining reference face.* In some cases, the machining reference face could also serve to maintain the stability of the part. Inui et al. (1985, 1987) have given some guidelines on how an initial selection of the candidates for the machining reference face may be done. Subsequently, the authors' system evaluates candidate faces for stability of the machined part when it is resting on any one of the candidate faces. Candidates with stability not good enough to support the part are eliminated from consideration. It is recommended that the workpiece be supported by a face with as few bounding faces as possible. Other resting faces of the workpiece are determined in the same manner.

A number of rules for part orientation planning have been proposed and formalized (Ferreira et al., 1985; Ferreira and Liu, 1988). One example of such a rule, as incorporated in a rule-based system by the authors is: "A workpiece is stable in an orientation if the vertical projection of its center of gravity passes through the convex

hull of its support (base) face." A convex hull is obtained by connecting the outer most vertices of a part. A number of "basic" and "optimizing" objectives are identified to search for solutions in a given situation. Depending on the particular manufacturing environment, the objectives can change. For example, in large-scale production, a maximum number of operations should be performed in one setting. However, ease of workpiece restraint is the primary objective in small-batch sizes. For machining to tight tolerance specifications, the attainable accuracy will dictate the orientation of the workpiece. Stability in the resting position, against gravity, becomes important for large and heavy workpieces.

Guidelines for setup selection, based on orientation and tolerance relationships, have been proposed by Boerma and Kals (1988, 1989). Their procedure incorporates the dual objectives of (1) reducing the number of "critical" tolerances in the geometrical relations between features belonging to the different setups, and (2) keeping the number of setups to a minimum. In order to compare the significance of the different kinds of tolerances in the relations between features, a nondimensional "tolerance factor" is introduced. It is assumed that the smallest tolerance factor determines the maximum permissible rotation and translation errors of the part during fixturing. The two features, related by the smallest tolerance factor, determine the two orientations of the setup base. The third orientation is selected based on the tolerance-factor relationship of a third feature with either of the first two. The procedure is somewhat simplistic because it ignores all tolerance relationships, except tolerances of position, parallelism, and perpendicularity.

5.7 FIXTURING FOR NC MACHINING

For a fixture to be cost effective, it has to be used for large-batch sizes or be adaptable to different part geometries. Welded fabrications are commonly used as fixtures in production shops; but such custom-built fixtures are relatively expensive and can be limited to a single application. To eliminate the need for single-purpose fixtures, the use of standardized fixtures is quite popular. Tombstone tooling blocks, angle plates, parallels, V-blocks, riser blocks, and subplates are the basic components of standardized fixtures (Gouldson, 1982; Boyes, 1986). A tooling block or a base plate can be mounted precisely on the machine table. These components have a predetermined grid pattern of tapped holes to accept studs, clamps, and other fixture components, as shown in Figure 5.16. The built-up fixture can be removed and replaced exactly in the same position on one or more machines. There is also the provision of a tram hole, which is a bushing in the fixture base, at some known distance from the part location point. The tram hole establishes that point on the fixture from which all part dimensions are based.

Subplates can aid in setup time reduction, because they are usually designed and manufactured for the customer's machining center. A subplate needs to be aligned with the machine axes, using an indicator in the machine spindle, only during the initial installation. Once the subplate is locked into position, the indicator is not used again. Each modular component of the fixture, which is dowel-pinned and screwed to the subplate, is accurately aligned with the machine axes.

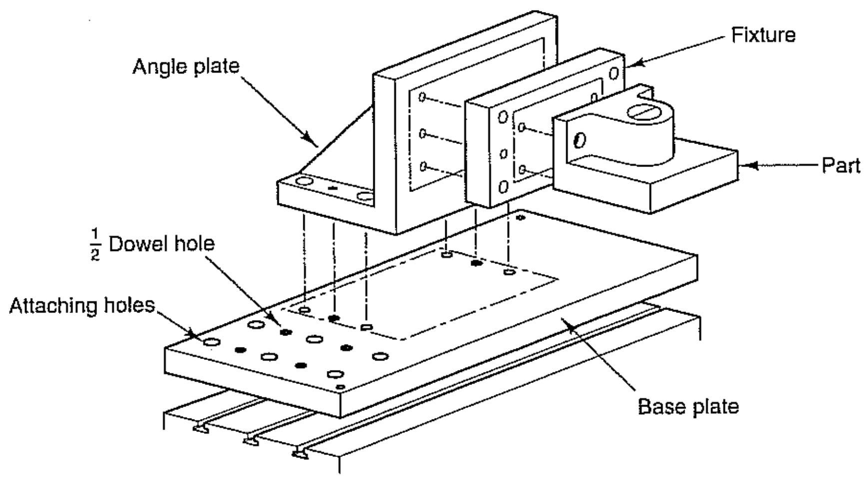

Figure 5.16 Assembly of standard fixtures (Gouldson, 1982).

The design of the fixture also depends on whether it is a first-operation fixture or a second-operation fixture (Gouldson, 1982). A first-operation fixture is used for a workpiece where no machining has yet been performed. These fixtures may be constructed using adjustable supports and locators in conjunction with a predetermined target point or line. If possible, a premachining operation is carried out on a conventional machine to establish a datum surface or locating holes. A second-operation fixture is used where some machining has taken place, so that reference surfaces or holes exist, which position the part with respect to the fixture and the fixture with respect to the machine table. Such fixtures are comparatively easier to design because an adequate reference surface is already available. Case studies on fixtures designed for NC machine tools can be found in Hatschek (1977).

A flexible manufacturing system (FMS) involves a group of CNC machine tools that perform a number of operations and manufacture many different parts. A material-handling system, such as an industrial robot, can transfer parts from one machine tool to another, provided the part geometry is not complicated. For heavier components and complex geometries, pallets are used. Fixtures are mounted on pallets that travel from one machine tool to another. Pallets, with the work material already loaded in fixtures, are held in the magazines of flexible manufacturing modules (FMMs), or in a central buffer store, from where they are delivered to the machines in the desired sequence (Karyakin, 1985). Multisided or cubic fixturing is frequently used where machine up time is important and the workpieces are relatively simple (Kellock, 1986). In a FMS, 2 to 12 components of the same type or different types can be loaded at one time for palletized transportation. Such an environment precludes the use of special-purpose fixtures from the cost viewpoint, because a large number of such dedicated fixtures would be required. This has lead to extensive research in adaptable, or flexible, fixturing.

A flexible (adaptable) fixture has been defined as a single device that holds parts of various shapes and sizes that are subjected to the wide variety of external force fields and torques associated with conventional manufacturing operations (Gandhi and Thompson, 1985a). Flexibility is a property of the fixturing device that makes it conform to the workpiece geometry. Flexible fixtures offer the following advantages (Thompson, 1984): (1) reduction in lead time and effort required for designing special fixtures; (2) lower overhead cost of storing a multiplicity of fixtures, which are required to effect rapid changeover between different manufacturing operations; and (3) simpler programming requirements. Designs of various "resettable" fixtures for use in a FMS have been proposed (Eremin, Lysenko, and Nemytkin, 1988). These fixtures have a common location scheme for a group of workpieces, and just resetting of the clamping element is required when a new workpiece is introduced. Some special problems encountered in building fixtures for the automated factory have been outlined by Bagchi and Lewis (1986). Zimmerman (1984) and Kuznetsov (1986) describe case studies on fixtures designed and built for use in FMSs. Noaker (1988) observes that, even though there has been ongoing R&D in flexible fixturing systems over the last 5 years, the most successful systems for tough problems have cost as much as the capital equipment.

Many different approaches have been tried in flexible fixturing, as shown in Figure 5.17. A number of individuals (Thompson, 1984; Gandhi and Thompson, 1985a; Grippa, Thompson, and Gandhi, 1988; Youcef-Toumi and Buitrago, 1988) have surveyed flexible-fixturing methodologies. Broadly, there are two major groups in flexible fixtures: discrete contact and continuous contact. In the discrete-contact type, there are a finite number of contact points that can be arranged in space to give different configurations. Continuous contact is one in which the number of contact points is infinite, such

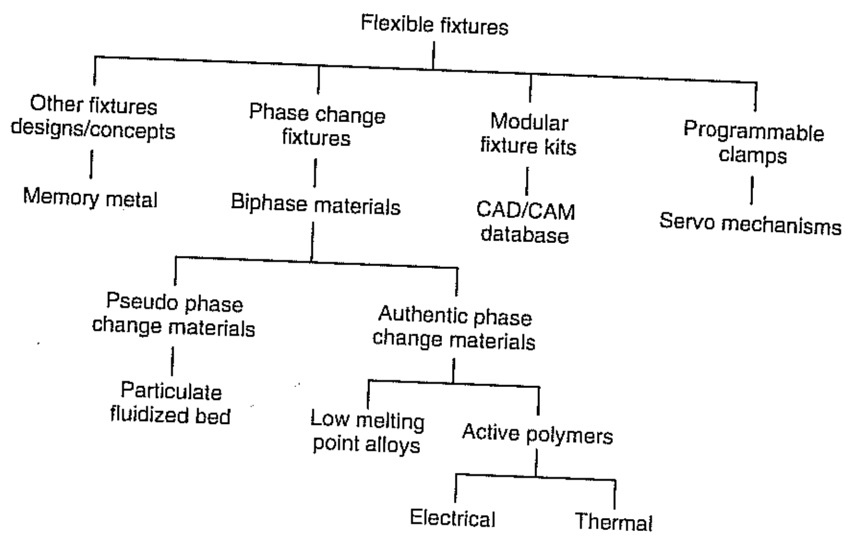

Figure 5.17 An overview of flexible fixturing methodologies (Gandhi, Thompson, and Maas, 1986).

as line or area contact. A point contact would completely constrain the motion in a direction normal to the workpiece surface only. Motions parallel to the workpiece surface would not be completely constrained, because of the limited friction in point contact. Surface contact would not only constrain the motion of the workpiece along the three axes, but also would constrain the applied moments. The following sections outline the salient features of some flexible-fixturing techniques.

5.7.1 Modular Fixtures

By incorporating a system of interchangeable and reusable components, it is possible to accommodate a wide variety of workpieces. Modular tooling systems use a system of individual components, which are assembled on a base, to suit the workpiece that requires fixturing. These systems are typically used for prototype tooling, short production runs for limited part quantities, or as a backup workholder to replace dedicated tooling that requires repair. By using a number of standard parts, and by eliminating the use of special parts as much as possible, the time required to design a complete workholder can be significantly reduced. The assembly time is also a fraction of the time required to build a dedicated fixture. Many companies have eliminated the use of dedicated fixtures, except where they are absolutely essential, and found considerable savings in modular tooling systems (Koch, 1988a, 1988b).

Modular fixtures permit the design of a fixture parallel with part design, because most modular system components can be accessed and retrieved from a CAD database. For example, elements of the CATIC modular fixturing system have been coded and stored in a database called PALCO-FIXTURE (Ranky, 1983). This fixture database incorporates graphics information and mating-surface descriptions for each element. Modifications in the modular fixture, due to alterations in the part geometry, are comparatively simple. Depending on the basic construction, modular fixturing is classified into three major systems: subplate system, T-slot system, and dowel-pin system.

Subplate systems are comprised of a baseplate or subplate to which all other components are attached. A subplate can be a simple plate, which is either drilled or tapped to accept threaded fasteners; or it can be machined with T-slots to accept nuts and bolts. The subplate may also be mounted vertically and may be single-sided or multisided. Subplate systems do not typically include accessories such as locators, supports, and clamps; these must be purchased separately. Common applications of subplate systems are for large parts, irregular parts, or short runs of simple parts. Parts can be mounted directly on the subplate, or the subplate can be used as a mounting device for other workholders such as box parallels, V-blocks, toolmaker's knees, and slotted angle plates. The Challenge System, ATCO System, Matrix Positioning System, Mid-state System, and Stevens Modular Tooling Systems are the premier systems in this category (Hoffman, 1987).

T-slot modular systems are rectangular, square, or round base plates across which T-slots are machined exactly perpendicular and parallel to each other. Round base plates usually have tangential and radial slots. T-slot systems are a complete fixturing set or system, that is, each element within the set is designed to be used to completely build or assemble an entire workholder. The advantage of T-slot systems is in the flexi-

bility of positioning the various component parts. Principal systems in this category are the Halder system (Krauskopf, 1984; Erwin Halder KG, 1987), CATIC modular fixturing system (Lewis, 1983; Xu et al., 1983), Warton Unitool system (Hoffman, 1987), Block Build Jig system 64 (Horic, 1988), and Cessloc system (Hoffman, 1987).

Dowel-pin modular tooling systems are the newest form of modular component tooling. Examples of this category are the QU-CO system (Qu-Co, 1987), Bluco Technik Modular system (Quinlan, 1984) SAFE system (Smith, 1982), and Yuasa Modula-Flex Fixturing system (Hoffman, 1987). All these systems use some combination of precisely positioned dowel holes along with tapped holes to accurately align, locate, and secure fixturing elements. These holes are arranged in a rectangular pattern in a base plate and larger structural elements. Like the T-slot systems, dowel-pin systems incorporate all locating and workholding elements into a single set. However, this set does not include the base plate, which the user can buy or machine separately. Dowel-pin systems have the advantage of consistently accurate placement of each fixturing element at fixed coordinate points, so these systems are ideally suited for use with CAD, NC machining, inspection systems, and for assembly by robots. Special T-slot overlay elements are available for dowel-pin patterns, giving both T-slot flexibility and dowel-pin accuracy (Quinter, 1988).

In addition to the base plates or mounting plates, modular fixturing elements include locating and supporting elements, mounting blocks, and clamping elements. The locating and the supporting elements closely resemble those used in conventional jigs and fixtures. Mounting blocks are a form of locating and supporting elements that are primarily used to position locators or clamping devices at specific heights off the mounting base. The commonly used clamping elements are strap clamps and screw clamps. Generally, all fixturing elements are made of high-grade alloy steel to tolerances of ± 0.005 to ± 0.01 mm in flatness, parallelism, and size. These tolerances assure accurate alignment and referencing. Modular fixtures are increasingly using some type of power clamping based on air or oil pressure. Devices for power clamping are clamping cylinders, swing clamps, rotating or pivoting clamps, retracting clamps, toe clamps, and power toggle clamps. Power-operated positioning and supporting devices are also commercially available.

A cost comparison for FMSs showed that modular fixturing yielded up to 75% savings over dedicated fixturing (Lewis, 1983). Significant reductions in lead times were also observed. Cost equations for economic justification of modular fixtures have been developed (Xu et al., 1983; Friedman, 1984).

5.7.2 Phase-Change Fixtures

This fixture type exploits the property of some materials to change from liquid to solid and back to fluid again. The workpiece is immersed to the desired depth in the material while it is still liquid. The special material is then changed to solid by altering certain conditions, and machining of the workpiece is carried out. To remove the workpiece from the fixture, the immersion material is liquified again. These materials may be of two kinds, those that undergo a pseudo phase change, like particulate fluidized beds, and those that undergo a true phase change, like low-melting-point alloys. The evaluation of

phase-change materials is based on the following properties (Gandhi and Thompson, 1984): (1) The phase change must be rapid, reversible, and uniform in space and time; (2) there should be no adverse effect on the geometry or surface properties of the workpiece; and (3) the power required to initiate the change of phase must be carefully quantified. Particulate fluidized bed fixtures (Gandhi and Thompson, 1985a, 1985b, 1986; Thompson and Gandhi, 1989) are based on the two-phase property of a particulate fluidized bed. As shown in Figure 5.18, the fixture consists of a porous bottom container that is filled with a spherical particle material. When air is supplied at a controlled rate through the porous base, the particulate bed achieves a fluid state of dynamic equilibrium, permitting the workpiece to be immersed. On switching off the air supply, the particles compact under gravity, thereby fixing the workpiece. After machining, the air supply is switched on and the workpiece is removed. This fixture falls in the intermediate category between the discrete-contact and the continuous-contact type of flexible fixtures. The degree of performance of this kind of fixture can be measured by its ability to resist extraction forces in the vertically upward direction, because lateral movement of the workpiece is already constrained by the compacted particulate bed. Experiments (Gandhi, 1986) indicate that extraction force F may be maximized by maximizing the depth of immersion, using a bed material of the largest specific weight, and by choosing a bed material with a high coefficient of friction for the given workpiece material. Mathematical models for calculation of extraction force F and computer simulations to examine the role of different bed-material parameters and loading conditions have been presented (Gandhi and Thompson, 1985b, 1985c; Thompson and Gandhi, 1989).

Low-melting-point alloys have been used to partially encapsulate the workpiece prior to machining. These bismuth-based alloys, which have melting points as low as 47° C, tend to expand on solidification. This technique has been applied to the manufacture

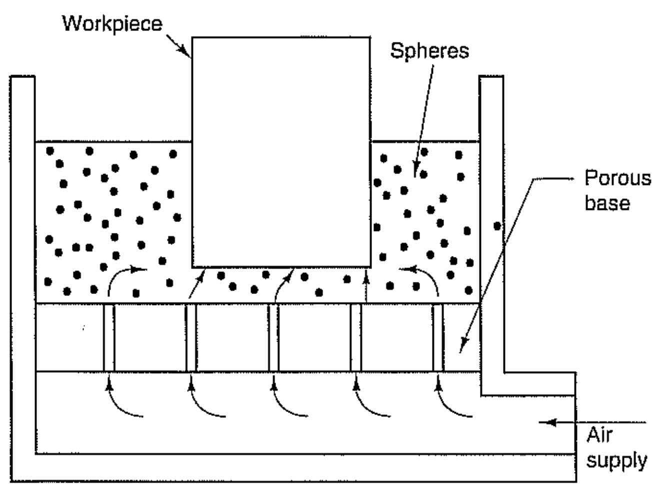

Figure 5.18 Schematic of a fluidized bed fixture (Ghandi, 1986).

of awkwardly shaped high-tolerance components, such as gas turbine and compressor blades (Nyamekye and Black, 1987), and for grinding wedges for milling cutters (Kellock, 1986). An injected metal encapsulation machine is the main feature of this system. The workpiece, which may be an unmachined blade, is precisely positioned with locators into a cavity in the machine prior to the injection of a molten alloy. As soon as the alloy solidifies, the encapsulated blade is ejected from the injection machine. The block of alloy is thus cast in a shape that gives the reference and clamping surfaces required during machining. After machining, the capsule is mechanically cracked open and the alloy is reused. Because a different die is required for each workpiece, the use of low-melting-point alloys is generally quite expensive.

Electrically induced phase-change fixturing (EPF) is an innovative concept that employs modern polymeric materials like polycrylonitile as the medium undergoing the phase change (Gandhi and Thompson, 1985b). In these materials, a phase change is induced by an electric field. This class of fixtures has the advantage of a limited compliance in the solid phase, which is beneficial in robot assembly.

5.7.3 Flexible Fixturing Requirements

Among other less common fixturing schemes are the Multi-Leaf Vise and the Petal Collet (Thompson, 1984), electromagnetic chucks (Kellock, 1985), magnetic cubical fixtures (Kellock, 1986), and electrostatic fixtures (Tazetdinov, 1969). A survey of various magnetic force applications in workholding has been conducted ("Magnetic Work Holding," 1974). Although the choice of a flexible-fixturing technique will depend on the application, it should satisfy certain requirements, in order to function successfully in a flexible manufacturing cell. Some key requirements are as follows (Youcef-Toumi and Buitrago, 1988, 1989):

1. *Reconfiguration of conformable surface:* The intermediate medium, between the rigid part of the fixture and workpiece surface, should have the dual properties of compliance and stiffness, with a quick "phase" change between the two.
2. *Clearance from machining paths:* Flexible fixtures, by their nature, tend to occupy larger surface areas of the workpiece in certain locations. Therefore, the design of the fixturing layout is more critical than in conventional fixtures.
3. *Clearance for workpiece loading/unloading:* The workpiece must be located and referenced to fixed supports, before the conformable surfaces of the fixture approach, to adapt to the workpiece surface. Thus, there should be provision of some initial reference surfaces to place the workpiece in the future.
4. *Ease of operation by a robot manipulator:* An example of this property can be found in modular fixtures where special mating surfaces and locking devices guarantee positive location of the modules, thereby significantly reducing the accuracy requirements of the robot.
5. *Actuation:* The fixture should be self-contained, that is, it should contain at least one actuation element that provides the fixturing force. Actuating forces could also be provided by a robot.

5.8 ERRORS DUE TO LOCATION, CLAMPING, AND MACHINING

Tolerances are specified on a drawing, because it is not possible to manufacture a part exactly to the specified dimensions. The zone, in which the outline of the finished part is to lie, is provided by the tolerance specification. A prismatic part may be considered to be placed in a system of three mutually perpendicular planes that are called *datums*. A datum is a theoretical plane from which dimensions are specified. The surface in contact with the datum is called the *datum surface*. Tolerances control not only the dimensions, but also the geometrical properties of the part, such as flatness, perpendicularity, parallelism, straightness, runout, and surface roughness. It is the primary objective of the process planner to produce the part to the desired tolerance (accuracy), and therefore any fixture design procedure will have to take tolerances into consideration.

Location (mounting) errors have a significant effect on workpiece accuracy. These errors may be considered to be the inaccuracy of the workpiece position with respect to the pallet surface, cutting toolholder, machine tool guideways, and so on. Rigidity of the locating elements and of the workpiece material will also give rise to mounting errors. For an analysis of rigidity effects, refer to the work of Shuleshkin and Gromov (1960). Another important source of inaccuracy is the nonsimultaneous application of clamping forces on the workpiece. Both mounting and clamping errors combine to result in tilting and turning moments and also shear forces that displace the workpiece with respect to the desired position. Bazrov (1982) has formulated criteria to show how the overall accuracy attained in machining is influenced not only by the precision mounting of the workpiece, but also by the choice of coordinate systems employed for setting the pallet, cutting tool, fixture elements, and so on. Analyses and experiments to study the influence of the sequence of clamping forces on the accuracy of the workpiece have been conducted by various investigators. Bazrov and Sorokin (1982) established how a rational sequence of clamping forces, force magnitudes, and friction coefficients may be selected to adjust the workpiece displacement in the desired direction. Experiments by Batyrov (1984, 1986) show that adverse quality of the surfaces in contact between the fixture and the workpiece may enhance the errors caused by clamps being actuated in a particular sequence.

For a part being produced on a machining center, the operations performed most commonly are side milling, end milling, and hole making. Knowledge of the process mechanics of each of these processes is vital to the fixture design process. Whereas a clamping force is static and fixed in both direction and magnitude, the cutting force is dynamic, with a magnitude and point of application that vary during the machining operation. These will require the development of rules or strategies to ensure that the position and orientation of clamps and supports will suffice to locate and hold the workpiece, so that it does not deflect more than a certain "critical" deflection. This "critical" deflection limit will depend on workpiece material properties and machining parameters. During the metal-removal operation, the workpiece deflects and assumes a certain profile. This is due to the bending and torsional deflection produced in the workpiece by the machining operation. After machining, the workpiece will "spring back" and assume a profile that will differ both from its original and from the one assumed during machining.

It is this final profile that will determine the acceptability of the workpiece in terms of the specified tolerances on its blueprint.

5.9 SUMMARY

In this chapter, the basics of tool engineering have been presented. Although several analytical models for jig and fixture design have evolved over the past decade, fixture design is still an "art" that can dictate the profitability of a manufacturing process. Tooling and fixturing also impose some of the most rigid flexibility constraints in today's flexible manufacturing environment.

REVIEW QUESTIONS

1. Define the following terms: rake face, flank face, rake angle, cutting edge, and shear angle.
2. Describe the situations in which positive and negative rake angles are used.
3. What are the major causes of rake wear and flank wear?
4. What is the purpose of coating HSS tools? What kind of materials are used in coating?
5. What are the most commonly used carbide substances for tools?
6. Why is a negative rake angle always used with ceramic tools?
7. What are the advantages of using ceramic tools?
8. What are the most commonly used criteria used in measuring machinability?
9. How does one determine that a tool has failed?
10. What is free-machining steel?
11. What is a jig and what is a fixture? What are they used for?
12. List important considerations in fixture design.
13. What is the 3–2–1 principle?
14. What are the 6 points in 3–2–1 used for?
15. After the six points have been determined, how do we ensure that the workpiece will not move?
16. What is the relationship between locating points and datum surfaces?
17. What is the basic principle in selecting supporting methods?
18. What is the principle in selecting clamping arrangements?
19. What is a modular fixture?
20. What are the advantages and disadvantages of using modular fixtures?
21. What kind of fixture is used in a flexible manufacturing system? What are the differences between this kind of fixture and conventional fixtures?
22. Design a fixture for the following operation: The flat surface of a disk 4 inches in diameter and 0.5 inch tall is to be milled. The disk is made of steel.
23. Design a fixture to hold the part shown in Figure 2.29.
24. Ten thousand of the parts shown in Figure 2.22 are to be machined. The true position tolerance is 0.001 inch. The operation needed is to drill the two holes. Design a jig/fixture for the process.

REVIEW PROBLEMS

1. Design a drilling fixture for the part shown in Figure 2.14. Assume that 5000 parts will be produced on a radial drill.
2. If the part shown in Figure 2.14 was to be a very low-volume part (only four to five parts were to be produced), what kind of fixture would be used?
3. Suppose the same part shown in Figure 2.14 was to be produced in high volume (more than a million), what kind of holding device and machine would be used?

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