CHAPTER 24
DRILLING PROCESSES

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24.1 INTRODUCTION

The purpose of through-hole drilling printed circuit boards is twofold: (1) to produce an opening through the board that will permit a subsequent process to form an electrical connection between top, bottom, and internal conductor pathways, and (2) to permit through-the-board component mounting with structural integrity and precision of location.

The quality of a hole drilled through a printed circuit board is measured by its ability to interface with the following processes: plating, soldering, and forming a highly reliable, nondegrading electrical and mechanical connection.

As with any process, the elements of the drilling process are:

- Materials
- Machines
- Methods
- Workers

When workers are properly trained and educated so that they possess a sound understanding of the other three elements, it is possible to drill holes meeting the aforementioned requirements with high productivity, consistency, and yield.

The goals of this chapter are as follows:

- Understanding the drilling process thoroughly
- Recognizing what might go wrong
- Locating where problems could occur
- Detecting whether problems do occur
- Finding root causes of problems
- Correcting undesirable conditions
- Striving for zero discrepancies
- Making improvement a team effort

24.2 MATERIALS

Materials that affect the drilling process are as follows and as shown in the fishbone diagram of Fig. 24.1.

- Laminate material
- Drill bits
- Drill bit rings
- Entry material
- Backup material
- Tooling pins

24.2.1 Laminate Material

A typical circuit board laminate panel consists of three basic components:

- Supporting fibers
- Resin
- Copper layers

The laminate substrate material is constructed of supporting fibers (most commonly a glass fiber weave) and a resin (most commonly an epoxy compound). Finished board thickness may range from 0.010 to 0.300 in or thicker, with the most common panel thickness ranging around 1⁄16 (0.0625 in).

24.2.1.1 Supporting Fibers. Generally, the larger the glass fibers in the weave, the lower the cost of the base material. However, larger fibers are less desirable from a drilling point of view because they are more likely to cause the drill bit to deflect, resulting in decreased hole

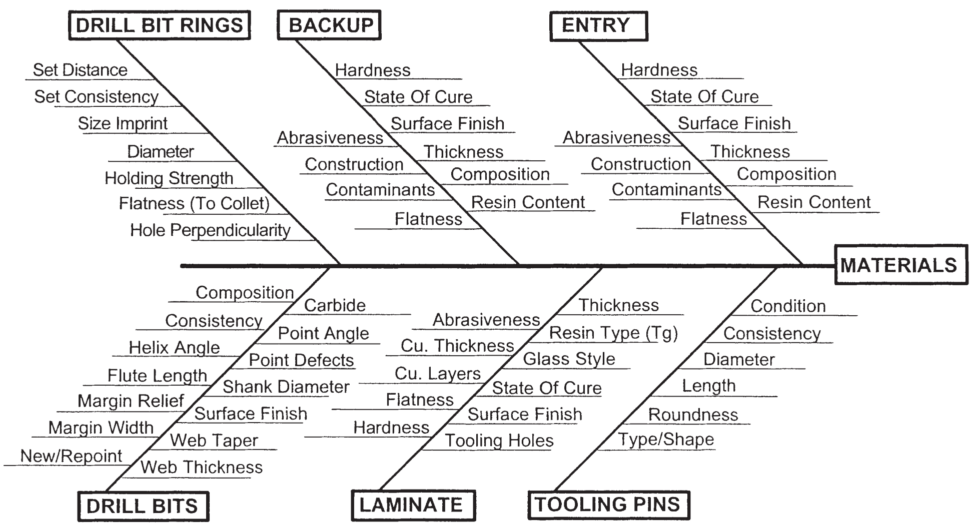


FIGURE 24.1 Materials used in the drilling process, with major variables and special considerations identified.

registration accuracy. In addition, larger fibers adversely affect drilled hole wall quality because they create larger (drilling) voids, defined as tear-out of supporting fibers. In simple terms: the larger the glass fibers, the larger the chunks torn out during drilling and thus the greater the hole wall roughness.

24.2.1.2 Resin. The most common resin system is FR-4 epoxy. However, general drilling considerations (see Fig. 24.1) are the same for all resin systems. The glass transition (T_g) rating of a material is defined as the temperature at which fully cured resin starts to soften. The T_g of FR-4 is typically around 130°C or higher. Many materials have resin systems that include additives or that are different from FR-4 resins (e.g., polyimide) in order to raise the T_g. The reason higher T_g is desired is because it implies a more stable material with lowered z-axis expansion rates. Although higher-T_g material may reduce the extent of hole wall resin smear, the compromise of a higher-T_g product is that the material is more brittle and more abrasive to the drill, resulting in increased tool wear and hole wall roughness. This increased abrasiveness to the drill bit may be offset by reducing the surface speed to reduce the spindle speed, resulting in less frictional heat being generated. Lowering drilling heat reduces drill wear.

24.2.1.3 Copper Layers. Outer and inner copper layers may be of various thicknesses, the most common being what is referred to as ½-oz and 1-oz copper. One-ounce copper equates to a thickness of approximately 1.4 mils (0.0014 in). The more copper layers within a laminate, the more balanced the panel from a drilling point of view, meaning reduced occurrences or extents of drilled hole defects such as voids (torn-out fiber bundles). However, in order to compensate for a greater number of copper layers, the chip load (advance per revolution) that determines the infeed rate usually needs to be adjusted to control nail-heading. Increasing the chip load reduces the amount of nail-heading. In addition, more copper layers wear the drill bit at a faster rate and may require lowering the maximum hit count per drill bit.

24.2.2 Drill Bits

24.2.2.1 Materials. Drill bits are made of tungsten carbide because its wear resistance (and relatively low cost) make it the most ideal material for cutting the very abrasive circuit board laminate materials. The compromise of this very hard (carbide) material is that it is also brittle and subject to damage in the form of chips if not handled carefully and correctly.

24.2.2.2 Handling and Inspection. When handling drill bits, do not permit the bits to come in contact with one another and be careful not to touch them to the sides of the tool pods. Modern drilling machines utilize drill cassettes to reduce time per load by eliminating manual tool changes. These cassettes may accommodate 120 or more drill bits and reduce drill bit handling damage. If drill bits are measured to verify diameter using a contact-type measuring device (such as a contact micrometer), take the measurement away from the point to prevent chipping of the cutting corners. Following diameter measurement, inspect the drill bit for damage using a microscope. After use, again use care when removing drill bits from the tool pods or cassettes and remember, if they are intended for repointing, to use the same careful handling practices as when they were new.

24.2.2.3 Geometric Attributes. The geometry of a drill bit very much affects the way it behaves during drilling. (See Fig. 24.2 for attribute nomenclatures.) The land is the area remaining after fluting. In order to reduce the amount of land that creates friction with the hole wall (thus generating heat), drill bits are margin relieved. The amount of land remaining in contact with the hole wall during drilling is referred to as the margin. The wider the margin, the greater the friction area and the higher the drilling temperature, resulting in higher extents of heat-related hole quality defects such as resin smear and plowing (defined as furrows in the resin).

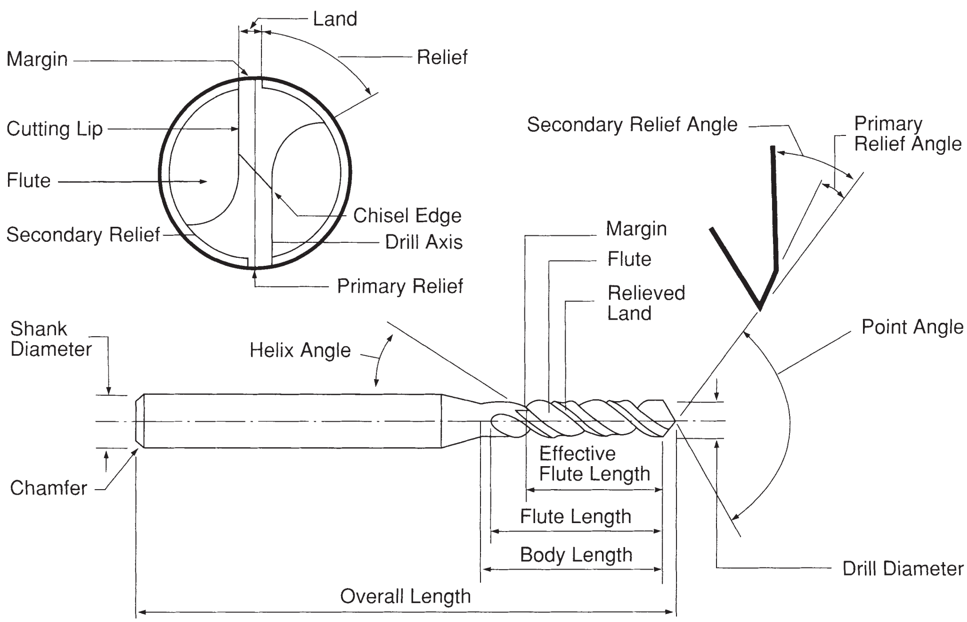


FIGURE 24.2 Drill bit geometry.

The result of increasing the land mass and the web is a smaller flute area. Less flute space implies reduced amounts of available area to remove drilling debris, which again raises the drilling temperature. It is important to understand that some drill designs that are meant to increase strength (particularly in smaller-diameter drill bits, with the intent to reduce breakage) may include what are referred to as partial margin reliefs (see Fig. 24.3). What this means is that when the drill bit is viewed from the point, a relieved margin is seen. However, viewing

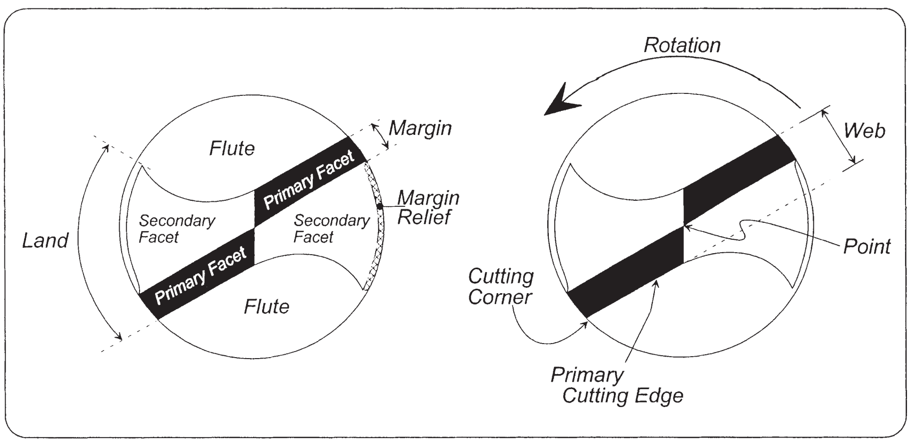


FIGURE 24.3 Drill tip attribute nomenclatures.

this type of design drill bit from the side reveals that the relief extends only part of the way, typically about one-fifth of the total flute length The major drawback of this particular design is that it increases drilling temperatures (documented to be as much as 25 percent or more), resulting in increased heat-related drilled hole defects (such as smear) and drill breakage due to packed margins.

24.2.2.4 Flute Length. Minimum flute length must equal total drilled depth (total laminate thickness + entry thickness + backup penetration depth) plus at least 0.050 in of unused drill flute remaining above the stack at the bottom of the drill stroke to allow debris to be removed by the vacuum system. If debris cannot be removed from the drill flutes during and between drill strokes, the results are extensive hole quality defects and drill breakage.

24.2.2.5 New Drill Bits. It is not necessary to inspect incoming orders of drill bits 100 percent. A procedure proved to be effective is to inspect drill bits according to an acceptable quality level (AQL) method (such as MIL-STD-105). This type of sampling plan allows the user to determine the percentage of drill bits that are inspected to judge an entire lot of drill bits to a predetermined quality level. Using this method, finding a defined quantity of drill bits that do not meet the specification is cause to return all received drill bits to the vendor; if the selected quantity of inspected drill bits meets specification, the entire lot of drill bits is accepted. Inspection criteria might include point geometry defects (refer to Fig. 24.4), damage (chips), diameter (drill and shank), and flute length, as well as correct ring set distance and size imprint (matching both the actual diameter and that labeled on the box).

24.2.2.6 Repointed Drill Bits. Drill bits are typically repointed for reasons of economics. The cost of repointing a tool may be as low as 15 percent of the cost of a new tool. The number of times a drill is repointed varies anywhere from 1 to as many as 10 times or more and typically depends on the drill diameter. The smaller the drill, the fewer times it is normally repointed. The reason is that smaller-diameter holes are more critical and require better hole quality.

There are two methods used to repoint tools.

1. The first is to specify a certain number of times the tool is to be repointed before being discarded. This number typically varies between one to three for smaller-diameter tools depending on hole quality experienced after repointing.
2. The second is to specify a minimum overall length of the tool at which it is discarded. Minimum overall length is determined by calculation based on minimum remaining flute length required to drill the required total drilling depth. This method does not allow determination of how many times a drill is actually repointed because stock removal during each regrind may vary from 0.002 to 0.005 in or more.

Repointed drill bits cannot be expected to perform as well as new drill bits because only the points are refurbished to a quality that may be as good as a new drill bit while the rest of the drill bit, including the critical margin, is not. The condition of the margin is very important because it is the part of the drill bit that finishes the hole wall. A rough margin results in a rough hole wall surface. When inspecting repointed drill bits, examine the sides of the drills for margin damage and/or fused or packed drilling debris remaining from previous use. These drill bits contaminate holes from the very first one drilled and may cause run-out due to an imbalanced condition of the drill bit resulting from the buildup. Drill bits must be repointed to the same point geometry specifications as those that apply to new drill bits. Point inspection criteria, therefore, is the same for repointed drill bits as for new drill bits.

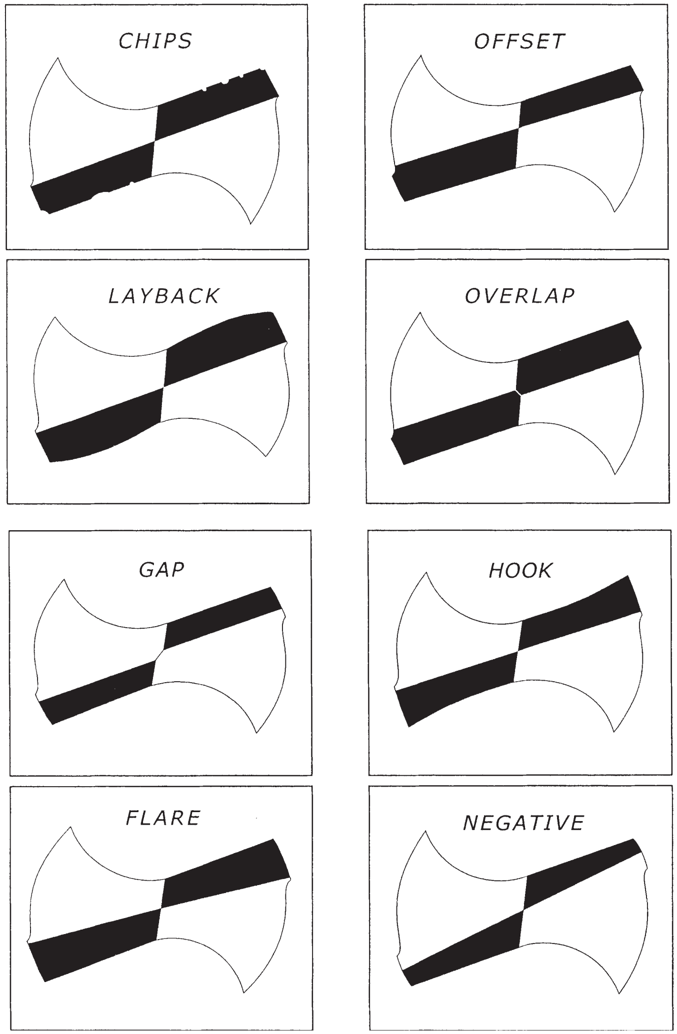


FIGURE 24.4 Drill point defect illustrations. (*Courtesy of LCOA Technical Center.*)

24.2.3 Drill Bit Rings

Drill bit rings are set to a common distance from the point to the back of the ring, thereby allowing a controlled drilling depth. The quality of these rings is as critical as the consistency of drill bit attributes because they can equally affect drill bit performance. Rings that fit loosely on the drill shank have been known to move during tool changes, resulting in insufficient drilling depth. Rings that fit too tightly may crack. Rings that have protruding material ("flash") on the inside diameter may cause improper seating of the drill bit in the collet (of the spindle) or may prevent the drill bit from being properly inserted into the tool pod or cassette, resulting in destructive tool change problems.

Rings have specific color codes assigned to each size and are commonly imprinted with size, diameter, and design or series number. Rings may be either machined or mold-injected. While machined rings are superior because of their consistency and quality, their cost is prohibitive for many drill bit manufacturers. Some of the drawbacks of mold-injected rings that must be monitored are inside diameter, affecting how well the ring fits on the drill shank, and remaining flash.

24.2.4 Entry Material

24.2.4.1 Purpose. The purpose of the entry material is fivefold:

- Centers the drill
- Prevents drill breakage
- Prevents copper burrs
- Avoids contamination of the hole or drill bit
- Prevents pressure foot marks

24.2.4.2 Types. There are many different available types (constructions) of materials used as entry material for printed circuit board drilling, although few are specifically designed and engineered for this purpose. Engineered products are designed to improve hole registration accuracy and reduce drill breakage. The performance qualifications of the most popular materials are discussed in the next section.

Commonly available entry materials, listed in order of performance quality with respect to the five characteristics listed in the preceding section, are:

- Aluminum-clad cellulose core composite
- Solid aluminum (various alloys and thicknesses)
- Solid or melamine-clad phenolic
- Aluminum-clad phenolic

24.2.4.3 Performance. The right entry material will improve drilled hole registration and lower the risk of drill bit breakage by minimizing drill deflection upon contact with the stack. In order for the entry material to function properly, it must be flat and free of pits, dents, and scratches. Warped or twisted material will result in increased extents of entry burrs and drill bit breakage. Surface imperfections and materials that are too hard contribute to drill deflection, resulting in decreased hole registration accuracy and breakage of small-diameter drills.

Phenolic materials or phenolic composites (i.e., aluminum-clad phenolic) often warp and under most drilling conditions contaminate the hole wall, which results in problems with adherence of the plating because desmearing chemicals are not designed to remove phenolic resin. Solid aluminum materials of the correct composition and hardness that are not of an excessive thickness, yet are not too thin, may work satisfactorily with larger-diameter drill bits. However, drilling with solid aluminum materials (0.008 in and thicker) may increase the risk of breakage of smaller-diameter drills. Aluminum-clad cellulose core materials provide a hard surface to prevent burrs yet minimize drill deflection and breakage associated with solid aluminum.

24.2.5 Backup Material

24.2.5.1 Purpose. The purpose of backup material is defined by the following criteria. An ideal backup material will:

- Provide a safe medium for drill stroke termination
- Prevent copper burrs
- Not contaminate the hole or drill bit
- Minimize drilling temperatures
- Improve hole quality

24.2.5.2 Types. Numerous materials are available that are sold as backup material. Few of the materials used as backup materials are actually specifically engineered for circuit board drilling. Many of the popular backup products are composites with a variety of surface coatings or skins bonded to several different core materials. Available backup products include the following:

- Epoxy-paper-clad, wood-core composite utilizing a bonding agent with lubricating properties
- Aluminum-clad, wood-core composite
- Epoxy-paper-clad, wood-core composite
- Melamine-clad, wood-core composite
- Urethane-clad, wood-core composite
- Solid phenolic
- Aluminum-clad phenolic composite
- Plain wood
- Hardboard

24.2.5.3 Performance. Desired qualities in a backup material are minimal thickness variations, flatness (no bow, warp, or twist), no abrasives or contaminants, a smooth surface, low cutting energy (minimizing drilling temperatures), and a surface hardness that supports the laminate copper surface (to prevent burrs) yet does not cause damage or extensive wear to the drill bit.

Backup materials with lubricating properties have been proven to significantly reduce drilling temperatures by as much as 50 percent or more, often resulting in temperatures below the T_g of the laminate product being drilled. This advantage greatly reduces hole wall defects such as roughness, smear, and nail-heading and often allows increased drill stack heights and/or greatly increased drill bit maximum hit counts. The importance of these benefits is significant reduction in drilling cost per hole and improved productivity and yield.

Remember that drilled backup debris exits the stacks by passing through the holes in the laminate material and that therefore contamination (from the backup material) is of great concern. Materials containing phenolic, or composed of solid phenolic, are not suitable for circuit board drilling. Phenolic materials or phenolic composites (i.e., aluminum-clad phenolic) often warp and under most drilling conditions contaminate the hole wall, which results in problems with adherence of the plating because desmearing chemicals are not designed to remove phenolic resin. Hardboard types of materials cannot be maintained to thickness variation tolerances acceptable for circuit board drilling and are a source for a great variety of contaminants (e.g., oils crystallized on the surface for hardening purposes).

24.2.6 Tooling Pins

Seldom is any due attention given to the tooling pins. They come in many shapes and sizes and their cost, with respect to how much they add to the cost of fabricating a circuit board, is insignificant. Yet, quite often, tooling pins are found to be damaged or deformed (e.g., "mushroomed" from being hammered into the stack) or do not fit snugly. Tooling pins that do not hold the stack tightly in place or that allow the stack to move create a large variety of problems from burrs and other hole defects to poor registration or drill bit breakage. These unnecessary problems may be prevented by simply replacing tooling pins when they start to show signs of wear or damage. Use tooling pins that are hardened to minimize wear and deformation, and (ideally) 3⁄16 in in diameter. Pins that are less than 3⁄16 in in diameter (i.e., 1⁄8 in) do not hold the stack firmly in place during drilling and may result in stack movement.

24.3 MACHINES

Machine variables that affect the drilling process are as follows and as shown in the fishbone diagram of Fig. 24.5.

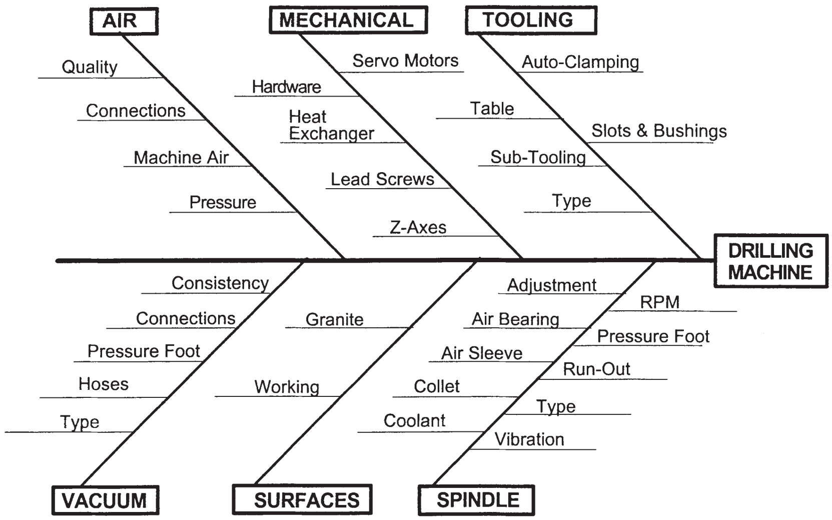


FIGURE 24.5 Drilling machine elements, with major issues and special considerations identified.

24.3.1 Air

24.3.1.1 Quality. Maintaining high levels of air quality is important. Air supplied to the machine and the spindle assemblies needs to be clean and dry. This is accomplished by filters that remove dirt and moisture from the air. In areas where the relative humidity is high, or when using air-bearing-type spindles, an inline air drying and filtering system may be necessary to control air moisture levels and dirt. Moist air causes corrosion of air surfaces (such as the spindle sleeve and other spindle components operating on air) and reduces the life of these components, resulting in increased repair costs. Dirty air affects operation of components relying on air by clogging the channels that supply the air (e.g., to the spindle sleeves and table air shoes). In addition, dirt serves as an abrasive that causes faster wear of machine components, resulting in reduced life cycles between repairs, again increasing downtime and repair costs. Cleaning the machine air filters and purging air compressors and lines on a routine basis may minimize problems resulting from dirt or moisture.

24.3.1.2 Connections and Pressure. Check connections, gauges, hoses, and switches for leaks and wear. Air hoses connected to the pressure foot pistons often crack near the piston connector; by simply bending the hoses in these areas it can be determined whether they are leaking. Other locations that commonly have poor connections and air leaks are the collet air connector on top of the spindle and the air manifold on the side of the spindle sleeve housing that supplies air to the collet and the spindle sleeve. Sufficient air pressure to both the collet and the spindle sleeve is critical and must be maintained adequately for proper operation. The tool table is designed to ride on a bearing of air supplied through the table air shoes. Verify proper operation of the air shoes by slightly rotating them back and forth; the shoes should move freely. If the shoes do not move with ease or do not move at all, the most likely reason is that the air channels are blocked due to trapped drilling debris, meaning the shoes need to be cleaned or replaced. Check the pressure foot air gauges for the correct air pressure; equal pressure must be supplied to each of the spindle stations. Insufficient or unequal air pressure results in burrs and increases the possibility of drill bit breakage.

24.3.2 Vacuum

Effective vacuum is absolutely essential because it greatly affects the resulting drilled hole quality. Heat (drilling temperature) seen by the hole walls depends on how effectively hot drilling chips are removed. Excessive temperature due to inefficient removal of drilling debris causes heat-related hole defects such as smearing and plowing, increases the opportunity for plugged holes, and is a major contributor to drill wear. Check hoses for proper connections, wear, and restrictions and examine the inside of the pressure foot for holes worn inside the connector attaching the vacuum hose.

24.3.3 Tooling

24.3.3.1 Bushings and Slots. Maintain tight tolerances on tool table bushings and slots and replace bushings that are sunken below the tool table surfaces or are worn. Bushings and slots that do not hold tooling pins snugly and allow stack movement during the drill stroke cause burrs, registration problems, and drill breakage.

24.3.3.2 Subtooling. Avoid subtooling plates that overlap across individual tool table stations and fasten the plates securely to the base plates with no separation or gaps. Ensure the subtooling is not warped, does not vary significantly in thickness, and has no surface protrusions (such as broken drill bits) to allow stacks to lay flat and to minimize variation in drill bit penetration depth into the backup material. If your subtooling is other than metal, watch for potential shrinkage or expansion problems indicated by difficulties in fitting the pinned stacks to the existing pinning holes in the plates. If this problem occurs, the results are the same as those caused by bushings and slots that allow stack movement.

24.3.4 Spindles

Spindle assemblies are one of the single most important components of the drilling machine. Proper operation is essential and requires maintenance (e.g., collet and collet seat cleaning) and verification on a regular basis.

24.3.4.1 Collet Maintenance. For mechanical (ball) bearing spindles, cleaning of the collet and the collet seat (inside the spindle) needs to be performed a minimum of once per shift; dirty collets increase drill run-out. When processing certain laminate materials that create greater amounts of drilling dust, and depending on your vacuum system efficiency, a higher cleaning frequency may be necessary to maintain acceptable levels of drill run-out. It is recommended that after cleaning the collets be returned to the same spindle from which they were removed because collets tend to adjust to the respective collet seats. For air-bearing spindles, most manufacturers recommend cleaning the collets only when the run-out measures excessive.

24.3.4.2 Run-Out Measurement. Drill/collet concentricity, or total indicated run-out (TIR), is a measure that indicates how true the assembly rotates. It can be determined while the spindle is running at various speeds (rpm), which is referred to as a dynamic form of measurement. Another method is performed while the spindle is not running and is called a static measurement. Static TIR is determined by rotating a ⅛-in (0.1250-in)-diameter pin installed into the collet by hand while reading movement on a dial indicator placed against the pin at a distance of approximately 0.800 in (simulating the distance of the drill point) from the collet nose (refer to Fig. 24.6). Of course, the pin used to measure TIR must itself be concentric.

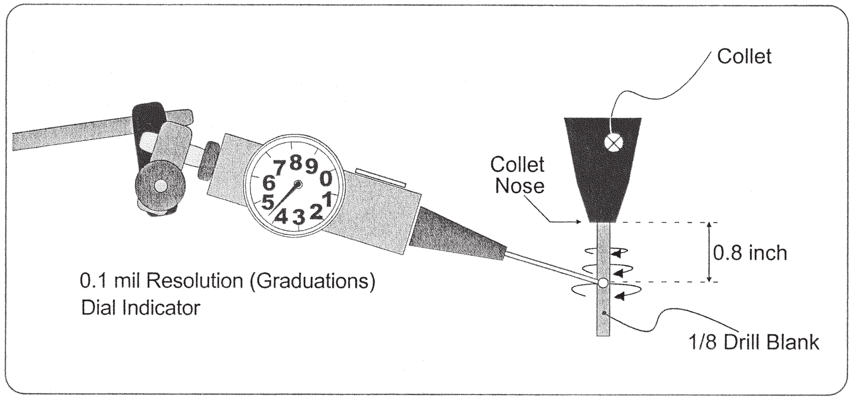


FIGURE 24.6 TIR measurement (static).

Maximum acceptable TIR for drills greater than 0.0200 in in diameter is 0.5 mils (0.0005 in). When using drills 0.0200 in or less in diameter, the maximum TIR needs to be maintained within 0.2 mils (0.0002 in) to prevent drill breakage. If excessive TIR is noted, it is wise to replace the pin and again measure the run-out. Drill bit blanks make ideal pins for measuring TIR and may be acquired from drill bit suppliers. Excessive spindle run-out results in drill breakage, causes burrs and other drilled hole defects, and adversely affects hole registration accuracy. Excessive TIR may often be corrected by simply cleaning the collet and the collet seat or by replacing a worn collet. Measure the run-out of spindles of each machine at a minimum frequency of once per week.

24.3.4.3 Spindle Speed. Maintaining correctly adjusted spindle speed is important because spindles running at speeds other than those displayed on the monitor imply that drill bits are rotating at surface speeds other than those that are desired. When actual rpm is higher than the displayed rpm, it implies higher surface speeds (refer to Sec. 24.4), and vice versa. Higher surface speeds cause greater frictional drill heat, resulting in faster drill wear and greater extents of heat-related hole defects such as smearing and plowing. Noncontact-type tachometers able to measure up to 150,000 rpm or more are available for around $300 (a lot less than the cost of rebuilding just one spindle) and allow measurement of actual spindle rpm in a matter of minutes. Verifying spindle speeds once every 6 months is usually sufficient.

24.3.4.4 Pressure Foot. The pressure foot insert lead distance to the point of the drill bit is set at approximately 0.050 in to give the pressure foot sufficient time to hold the stack flat before the drill bit contacts and enters the stack. If the lead distance is significantly less than the specified distance or if the drill bit point protrudes from the pressure foot, drill bits will break. To ensure the pressure foot assemblies function properly, check pressure foot inserts for wear or damage daily and verify that the pistons and guide rods are not bent and move smoothly.

24.3.4.5 Adjustment. When adjusting the physical *z*-axis height of the spindle, for instance to accommodate a thicker subtooling plate, care must be taken to also adjust the pressure foot so its height remains identical relative to the spindle. The pressure foot adjustment is independent from the spindle and, if not performed correctly, may result in a gap between the bottom of the spindle casing and the top of the pressure foot window. This gap is noticed only while the spindle is engaged and will draw most of the vacuum air, effectively cutting off the vacuum from the pressure foot insert, resulting in a great variety of hole defects and drill bit breakage. If a gap is present, it is usually accompanied by great amounts of drilling debris spewed across the stacks and drilling machine.

24.3.5 Mechanical Factors

24.3.5.1 Heat (Coolant) Exchanger. Drill motor temperatures are reduced by exchanging a fluid through the spindles. The fluid is processed through a heat exchanger that works much like a car radiator. As with a car, it is important to maintain the recommended coolant mixture, proper fill level, and flow rate indicated by the flowmeter. Check the operation of the fan and minimize coolant flow restriction (due to algae buildup) by cleaning filters regularly. Algae growth is promoted through exposure to ultraviolet light and may be controlled by using black hoses instead of clear ones in addition to adding growth inhibitors to the coolant mixture.

24.3.5.2 Hardware. Although simple to perform, checking mechanical connections for loose or worn parts (i.e., causing travel slop of pressure foot assembly movement) is often neglected. It may be accomplished by observing the machine while it is running or checking by hand while the machine is idle.

24.3.5.3 Lead Screws and Servos. The environment and cleanliness of the drill room determine how often lead screws need to be cleaned and lubricated to ensure smooth operation and minimize wear. Most machine manufacturers recommend performing this type of maintenance every 6 months. When lubricating the lead screws, only a light coat of the appropriate grease needs to be applied. Excessive amounts of grease on the lead screws defeat the purpose, as this causes more dirt to be attracted, resulting in faster wear. Constant searching for programmed *x*-*y* locations indicates problems with the servo motors or lead screws. If this occurs, the displayed *x* or *y* (actual) location displayed on the controller will change continuously while the machine is stopped.

24.3.5.4 z-Axis Stroke. Because machines may have as many as six mechanical connections in the *z* axis, travel slop during the drill stroke or retraction may occur, causing chip loads to vary during the stroke, which results in burrs and other hole defects and drill breakage. Check connections by hand for slop while the machine is idle and observe and listen for improper operation while the machine is running.

24.3.6 Surfaces

A clean drilling room decreases repair costs and the possibility of improper operation of the drilling machines. Wipe surfaces clean using a lint-free cloth or use a vacuum to remove debris.

Never use compressed air to clean the drilling machine because debris will be blown into areas that need to be kept clean (e.g., lead screws).

24.3.6.1 Granite. Granite provides a stable platform that absorbs unwanted vibration. It also offers a smooth and level surface to support the movement of the table. Keep granite surfaces clean to prevent tool table air shoes from becoming clogged and to minimize collection of dirt on the lead screws.

24.3.6.2 Working Surfaces. Maintain clean working surfaces, such as the tool table, to minimize the possibility of dirt particles getting trapped between the stacked laminate, entry, and backup panels, causing stack separation that may result in burrs and possible drill bit breakage.

24.4 METHODS

Drilling parameter variables that affect the drilling process are as follows and as shown in the fishbone diagram of Fig. 24.7.

24.4.1 Surface Speed and Spindle Speed

As holes are getting smaller, higher spindle speeds are required to achieve the desired surface speed that determines throughput. However, higher surface speeds result in higher drilling temperatures that may increase heat-related hole defects such as smearing and plowing.

24.4.1.1 Definition. Surface speed is a measure of how much distance is covered by the drill's diameter while it is rotated by the spindle and is expressed in surface feet per minute (sfm). It is used to calculate spindle speed (rpm) for a given drill diameter. The formula to calculate spindle speed using the desired surface speed is shown in Eq. (24.1).

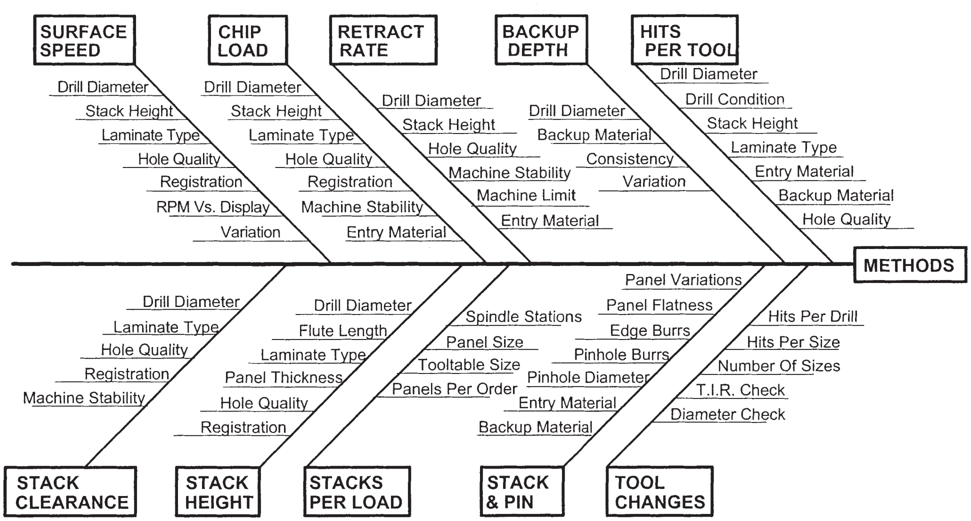


FIGURE 24.7 Methods used in the drilling process, with major variables and special considerations identified.

$$\text{spindle speed (rpm)} = \frac{\text{sfm} \times 12}{\pi \times \text{diam.}} \tag{24.1}$$

where diam. = drill diameter (in)
$\pi = 3.1415$

24.4.1.2 Effects. The higher the surface speed, the higher the spindle speed, and subsequently the higher the frictional heat that is generated, translating into greater extents of heat-related hole defects and drill wear. Conversely, lower surface speeds imply lower spindle speeds and less frictional heat. When more abrasive materials (e.g., materials with higher T_g such as multifunctional FR-4, polyimide, or cyanate ester) are processed or drilled stack height is increased, drilling temperatures increase. To offset the resulting increase in temperature under such conditions or when excessive extents of heat-related hole defects are apparent, decrease the surface speed to lower the spindle speed.

24.4.2 Chip Load and Infeed Rate

24.4.2.1 Definition. Chip load is defined as advance per revolution and is usually expressed in mils (1 mil equals 1⁄1000 of an inch [0.001 in]). It implies the distance the drill travels during the drill stroke per each full revolution of the drill bit. Chip load is used to calculate the infeed rate in inches per minute (ipm).

$$\text{infeed rate (ipm)} = \text{chip load (mils/revolution)} \times \text{rpm} \tag{24.2}$$

24.4.2.2 Effects. Higher chip loads result in greater throughput. However, chip load and infeed rate affect hole registration accuracy, drill breakage, burrs, and mechanical types of drilled hole defects such as voids (tear-out of the supporting fibers) and nail-heading. Faster infeed rates translate into higher (top laminate) entry burrs, lower extents of nail-heading defects and (bottom laminate) exit burrs, increased occurrences of drill bit breakage, and higher extents of drilling voids. Lower infeed rates result in exactly the opposite but lower throughput.

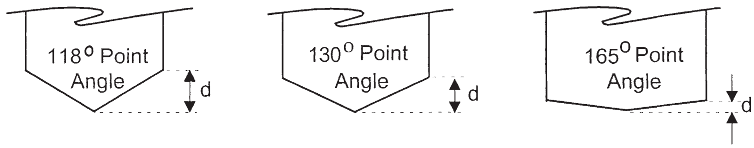
24.4.3 Retract Rate

24.4.3.1 Definition. Retract rate is the speed at which the drill bit exits the stack following the drill stroke and is expressed in inches per minute (ipm). Machine default (maximum) settings vary between manufacturers and may range anywhere from 500 to 1000 ipm.

24.4.3.2 Effects. Higher retract rates imply lower processing times per load. While the maximum retract rate setting may be fine for larger-diameter drill bits, when using drill bits in the diameter range of 0.0250 in (size #72) to 0.0135 in (size #80), retract rates may have to be reduced to 500 ipm or lower to prevent drill breakage. When drilling with sizes smaller than 0.0135 in in diameter, retract rates may have to be reduced even further. The maximum retract rate that may be used with any given drill diameter without causing drill breakage greatly depends on the stability and vacuum system efficiency of the drilling machine as well as the drilled stack height, laminate construction and thickness, type of entry material, use of proper stacking and pinning procedures, and the design characteristics of the drill bit such as flute length, web thickness, and web taper.

24.4.4 Backup Penetration Depth

24.4.4.1 Definition. Backup depth is the distance a drill bit penetrates the backup material at the bottom of the drill stroke. The minimum backup penetration depth setting varies depending on drill diameter and is determined by calculating the drill bit point length (see Fig. 24.8) and adding approximately 0.010 in. As a rule of thumb, backup penetration depth may be set to a distance equal to the drill diameter or 0.040 in, whichever is less.



d(118) = tan 31 x Radius = ~ .600 x Radius or ~ .300 x Diameter
d(130) = tan 25 x Radius = ~ .466 x Radius or ~ .233 x Diameter
d(165) = tan 7.5 x Radius = ~ .132 x Radius or ~ .065 x Diameter

FIGURE 24.8 Point length calculation.

24.4.4.2 Effects. Excessive backup penetration depth increases drill wear and the occurrence of breakage of small-diameter drill bits, adversely affects hole quality, and increases process time per load. Insufficient backup penetration depth results in incompletely drilled holes. This implies that thickness variations of the backup material are very important, meaning that minimal variations are a much desired characteristic of the backup and need to be considered when choosing a material suitable for your application.

24.4.5 Hits Per Tool

24.4.5.1 Definition. The maximum hits per tool specified for any given drill size implies the number of drill strokes a drill bit is used for until its expected effective life is expired. Maximum hit count per tool is product and process specific and is affected by laminate material construction, panel thickness, drilled stack height, surface speed, and the type of entry and backup material used. Therefore no specific number of hits per tool can be arbitrarily specified.

24.4.5.2 Effects. Excessive drill wear caused by excessive maximum hit count increases drilled hole defects and may prevent proper repointing. Conservative maximum hit counts greatly impact drilling cost per hole and increase time per load because of increased numbers of tool changes.

24.4.6 Stack Clearance Height

24.4.6.1 Definition. Stack clearance height is the distance between the point of the drill and the surface of the stack at the top of the drill stroke. Maintain a minimum stack clearance distance of ⅛ in (0.125 in), which implies a space between the bottom of the pressure foot and the top of the stack of 0.075 in, assuming the pressure foot lead distance to the point of the drill is correctly set at 0.050 in. Stack clearance may be adjusted for each load by simply sliding a 0.075-in shim between the pressure foot and the stack and adjusting the upper limit ("UP#") until the pressure foot touches the shim.

24.4.6.2 Effects. The less the stack clearance distance between the drill point and the top of the stack, the shorter the drill stroke and therefore the shorter the processing time per load. Increasing the stack clearance distance allows more time between drill strokes and gives the tool table more time to settle, which may improve hole registration accuracy and prevent small-diameter drill bit breakage. In addition, the greater the time between drill strokes, the more likely drilling debris will be removed from the drill flutes and, consequently, the lower the drilling temperatures, which results in reduced occurrences of drill breakage and lower extents of drilled hole quality defects.

24.4.7 Drilled Stack Height

Material construction (panel thickness, number of copper layers, laminate type, etc.), drill bit diameter, and flute length, as well as hole quality and registration accuracy requirements, all are factors that need to be considered when deciding on appropriate drilled stack heights. A greater number of panels in the drilled stack means higher drilling temperatures, accelerated drill wear, and greater drill deflection, affecting the resulting hole quality and registration accuracy. When using smaller-diameter drill bits, stack heights need to be reduced to prevent drill breakage and to accommodate the shorter flute lengths. As a rule of thumb, the maximum total drilled depth (number of panels × panel thickness + entry thickness + backup penetration depth) that can safely be handled by the drill bit without breakage is approximately 17 times its diameter.

24.4.8 Stacking and Pinning

24.4.8.1 Building the Stack. Inspect all laminate panels and the entry and backup materials for surface damage and remove burrs from the panel edges as well as from the pinning holes. Even though the registration tooling holes on the laminate material may not be used to pin the stacked panels together, it is important to remove any resin buildup remaining around these holes after lamination (a common occurrence). Burrs and raised surface areas do not permit the panels to lay flat, causing gaps resulting in drilled hole registration problems, burrs, hole quality defects, and drill breakage. Reject entry and backup materials with excessive nicks, scratches, and other surface defects as well as those that are warped or twisted.

24.4.8.2 Pinning Procedures. Wipe the surfaces of all laminate panels and the backup material using a lint-free cloth to remove any debris before stacking the panels (allowing intimate contact between the stacked panels). Verify that the pinning holes and pin insertion are perpendicular to the stack and avoid using pins that are damaged or deformed.

24.4.8.3 Installation. Before placing the pinned stacks onto the drilling machine tool table, inspect the surface for burrs or broken drill bits protruding from the table that may prevent the stacks from lying flat. Do not continue if the pin bushings of the tool table are sunken or worn to the point that they do not hold the stack firmly in place. Loose or sunken tooling pin bushings cause movement of the stack during drilling and result in a variety of hole defects, registration problems, and drill breakage, yet are simple to replace at a minimum cost. After stacks are put in place, again wipe the surface of the top laminate material as well as the entry material. Place the entry material on top of the stack and tape it in place. The entry material size should be such that it clears the pins and does not extend beyond the stack edges. Pinning the entry material to the stack is not recommended because it tends to constrict the movement of the material, causing separation between it and the stack and resulting in entry burrs and possible drill breakage.

24.5 HOLE QUALITY

24.5.1 Definition of Terms

The terms in Tables 24.1 and 24.2 are commonly used to describe drilled hole defects observed on copper and substrate surfaces. It is important to be able to identify these defects specifi-

TABLE 24.1 Copper Defects

Defect	Definition	Type
Burr	Ridge left on external surface	Mechanical
Debris	Drilling residues	Mechanical
Delamination	Separation of the copper from the substrate	Mechanical/heat-related
Nail-heading	Burr on internal copper layer	Mechanical/heat-related
Smearing	Thermomechanically bonded resin deposit	Heat-related

TABLE 24.2 Substrate Defects

Defect	Definition	Type
Debris pack	Drilling residues packed into voids	Mechanical
Delamination	Separation of the substrate layers	Mechanical/heat-related
Loose fibers	Unsupported fibers in the hole wall	Mechanical
Plowing	Furrows in the resin	Heat-related
Smear	Thermomechanically bonded resin deposit	Heat-related
Voids	Cavities due to torn-out supporting fibers	Mechanical

cally rather than in general terms. Using a general term such as *roughness* may imply voids or plowing. While voids are a mechanical type of defect, plowing is a heat-related type of defect. Therefore, excessive voids would lead one to examine the chip load (infeed rate) used; plowing would lead one to look at surface speed (spindle speed).

24.5.2 Examples of Drilled Hole Defects

Examples of typical drilled hole wall defects are shown in Figs. 24.9 and 24.10.

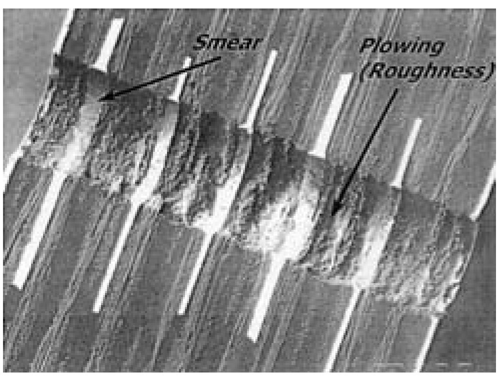


FIGURE 24.9 Cross section of drilled hole showing examples of smearing and plowing.

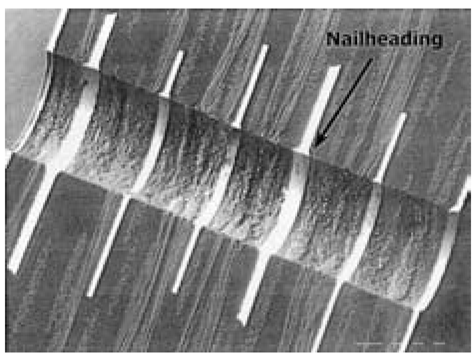


FIGURE 24.10 Cross section of drilled hole showing examples of nail-heading.

24.6 POSTDRILLING INSPECTION

A wealth of information is available by simply examining the materials from the drilled stack and the drill bits. For instance, inspecting the drill bits will allow one to determine if wear occurs at consistent rates (for drills of same diameter) or will reveal whether hit count maximums are excessive and the type of drilled hole wall defects to expect. Bonded debris and/or extensive wear to the drill corners imply high drilling temperatures (resulting in greater extents of defects such as smearing and plowing) or materials that are not fully cured and point to a problem with the materials (laminate, entry, or backup) or may suggest an excessive surface speed.

Extensive primary cutting edge wear indicates abrasive materials and may require lowering stack heights, reducing hit counts, or replacing entry or backup materials.

Burrs on the surfaces within the stack mean that there is a problem with the way panels are assembled and pinned or may be the result of warped panels. Entry or exit burrs on the outer laminates should cause one to question the entry and backup materials or the infeed rate.

The point of a postdrilling inspection process is that if one takes the time on a regular basis, to examine materials and drill bits after drilling, many drilling problems would be solved before they get out of hand.

24.7 DRILLING COST PER HOLE

Material and processing costs, as well as the resulting total drilling cost, may be determined by using an analysis matrix such as a cost model specifically designed for this purpose and generated with the use of a computer spreadsheet program. The advantage of using a spreadsheet is that it allows changes to be made in, for instance, specific material prices and processing times or parameters, and allows instantaneous viewing of the resulting effects on the total drilling costs, the cost per panel, and the average cost per hole. Knowing the cost per hole is important because it allows comparing different jobs or processing situations. Following is a step-by-step description of how to construct a drilling cost analysis matrix such as the one shown in Fig. 24.11.

24.7.1 Machine Time

Table A in the drilling cost analysis matrix is used to calculate the total time that is required to complete the job. First, the different drill sizes (a) and their respective total drilled holes per panel (b) as well as the total number of panels (c) to be drilled are determined and entered in the spreadsheet; this allows the spreadsheet to calculate the total number of holes for each size to complete the job (d).

Second, using the appropriate drilled stack height (e), the total number of drilled stacks (g) and the total number of drilled hits per drill size (f) can be calculated. The total number of drilled hits (drill strokes) is the total number of drilled holes per panel (b) divided by the number of panels per drilled stack (e).

Third, the number of total drilled stacks (g) is divided by the number of stations per machine (stacks per load [h]) to calculate the number of machine loads (i).

Fourth, the total drill time per load required per drill size (j) is entered to calculate the total machine time for each drill size (k).

Fifth, the total times of each of the drill sizes are simply added up to arrive at the total time required to finish the job.

An option is to enter the total drill time per load instead of entering the time for each of the drill sizes and multiplying the total drill time per load by the number of machine loads to determine total machine time.

TABLE A Machine Time

a	b	c	d	e	f	g	h	i	j	k
Drill bit size	Number of holes per panel	Number of drilled panels	Total number of drilled holes	Panels per drilled stack	Total number of drilled hits	Total number of drilled stacks	Stacks per machine load	Number of machine loads	Drill time per load (h)	Total machine time
0.0135	7,000	120	840,000	2	420,000	60	4	15.0	1.12	16.80
0.0160	5,000	120	600,000	2	300,000	60	4	15.0	0.80	12.00
0.0225	3,125	120	375,000	2	187,500	60	4	15.0	0.48	7.20
0.0350	1,500	120	180,000	2	90,000	60	4	15.0	0.19	2.85
0.0520	800	120	96,000	2	48,000	60	4	15.0	0.10	1.50
0.0700	250	120	30,000	2	15,000	60	4	15.0	0.04	0.60
	17,675		2,121,000						2.73	40.95

TABLE B Drill Bits

l	m	n	o	p	q	r	s	t	u	v
Drill bit size	Cost per new tool	Cost per repoint	Number of repoints per tool	Total cost per drill bit life	Number of uses per drill bit life	Average cost per drill bit use	Total number of drilled hits	Number of hits per drill bit use	Total number of drill bit uses	Total drill bit cost
0.0135	$1.25	$0.25	2	$1.75	3	$0.58	420,000	1,000	420.0	$245.00
0.0160	$1.20	$0.25	2	$1.70	3	$0.57	300,000	1,000	300.0	$170.00
0.0225	$1.15	$0.25	3	$1.90	4	$0.48	187,500	1,250	150.0	$71.25
0.0350	$1.15	$0.25	3	$1.90	4	$0.48	90,000	1,500	60.0	$28.50
0.0520	$1.15	$0.25	4	$2.15	5	$0.43	48,000	2,000	24.0	$10.32
0.0700	$1.30	$0.25	4	$2.30	5	$0.46	15,000	2,500	6.0	$2.76
										$527.83

TABLE C Entry and Backup Material

	w	x	y	z	aa
Material type	Cost per ft^2	Stack size ft^2	Cost per stack*	Total number of drilled stacks	Total material cost
Entry material	$0.53	3.00	$1.59	60	$95.40
Backup material	$0.65	3.00	$0.98	60	$58.50
					$153.90

* Backup material = cost/2 (uses per panel)

TABLE D Labor and Burden

	ab	ac
	Cost per hour	Cost total
Labor	$15.00	$614.25
Burden	$10.00	$409.50
		$1,023.75

TABLE E Total Costs

Cost variable	Cost per panel	Total cost	% of total
Drill bits	$4.40	$527.83	30.9%
Entry material	$0.80	$95.40	5.6%
Backup material	$0.49	$58.50	3.4%
Labor	$5.12	$614.25	36.0%
Burden	$3.41	$409.50	24.0%
Total drilling cost	$14.21	$1,705.48	100.0%

TABLE F Drilling Costs

Drilling cost per panel	$14.21
Average cost per 1000 holes	$0.804

FIGURE 24.11 Drilling cost analysis matrix. (*Courtesy of LCOA Technical Center.*)

24.7.2 Drill Bits

The cost of the drill bits needed to complete the job may be determined after the average cost per drill bit use has been calculated. To find the average cost per drill bit use, the typical number of repoints for the particular size (o) is multiplied by the cost of each repointing (n). The resulting cost, added to the new drill bit price (m), is the cost per drill bit life (p). By dividing the cost per life by the number of uses (q) per life (the number of times the bit is repointed + 1), you arrive at the average cost per drill bit use (r). Next, by dividing the total number of hits per drill size (s) by the number of maximum hits per drill bit use (t), the number of required drill bit uses (u) for each size may be determined. Then calculate the total cost per drill bit size (v) by multiplying the number of uses (u) by the average cost per use (r). The sum of the total costs of each of the drill bit sizes (v) brings you to the total cost of drill bits needed for the job. This cost, of course, is true only with the assumption of no drill bit breakage.

24.7.3 Entry and Backup Materials

Entry and backup material cost per stack (y) is determined by multiplying the stack size (square foot per panel [x]) by the cost per square foot. Remember to divide the backup cost by 2 since each backup panel may be used twice. Total material cost (aa) is calculated by multiplying cost per stack (y) by total number of drilled stacks (z).

24.7.4 Burden and Labor

Using typical burden and labor rates per hour (ab), these values are multiplied by the number of hours to complete the job (determined in Table A) in order to calculate the total burden and labor costs (ac).

24.7.5 Total Drilling Cost and Cost per Hole

After entering the required data in Tables A through D of Fig. 24.11, the total drilling cost and the cost distribution (see Table E) as well as the drilling cost per panel and the cost per hole (see Table F) can be calculated. Because the cost per hole typically ranges around $\frac{1}{10}$ of a cent, a more accurate and easier way to comprehend this value is by showing the average cost per 1000 holes, as is done in the cost model.

Next Chapter