Process Analysis for Optimization & Pollution Prevention

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Using process analysis is a key for implementing controlled changes to incorporate new technology and comply with regulatory requirements. Whether the goal is to increase efficiency, improve product quality or reduce environmental impact, an in-depth understanding of the current process is essential for adequately planning and implementing change.

Cost and availability of raw materials, and pressure from the federal government to limit emissions of hazardous materials used in manufacturing, have resulted in increased focus on production processes. Specific high-risk materials, such as polychlorinated biphenyls (PCBs), fluorocarbons and cadmium, have been targeted for elimination or reduction in use. Initiatives such as the Clean Water Act, Clean Air Act, and Occupational Safety and Health Act have caused an increase in the quantity and complexity of the control devices required to reduce process emissions. These devices have been effective in pollution control and health and safety exposures, but at considerable expense. Government regulations have led to recycling and source reduction as alternatives to end-of-pipe treatment. These approaches can be less costly, conserve raw materials, and make processes more efficient. Reducing costs and improving products have always been incentives for process optimization.[1,2] Employee safety and environmental protection, however, have added new terms to the equation, making process analysis more complicated.

Industry has responded to the regulatory pressures with an array of new equipment and chemistries. Interestingly, the surface finishing industry has been generally willing to embrace complete process substitution, but has shied away from changes to existing processes that would make them more efficient and “friendly.” There is fear that changes may destroy product quality. Surface finishers have been using processes developed over the course of the twentieth century, often empirically. Many times evolution occurred with only a basic understanding of the chemistry involved. Control of all variables in a multi-step, multi-component experiment is difficult.[3] At many facilities, the person who developed the process is no longer involved with the business. Formal procedures may not exist, and daily operations do not encourage in-depth knowledge of the process. These factors combine to form the “shop lore” and create the sense of impending doom when changes are suggested.

Fixing a Problem Can Create Others

Outside influences can force change before all aspects of the problem are considered. As an example, many surface finishers are attempting to limit usage of hydrofluoric acid because of health and safety hazards. Generally, process solutions using hydrofluoric acid may be more safely made up and maintained with ammonium bifluoride as the source of hydrofluoric acid. The release of hydrofluoric acid from ammonium bifluoride also generates dissolved ammonia, which can be a problem in wastewater. The dilemma is whether it is more effective to use hydrofluoric acid and deal with minimizing employee exposure, or deal with the difficulty of removing the ammonia from wastewater. Finding the answer leads to the first steps in a complete process analysis—identifying the drivers for change and defining goals for the outcome.

Another key to process analysis is process knowledge.[4] Currently, most process development is carried out by vendors. Developments in equipment and chemistries add new control requirements to various points of the process. In-depth understanding of the implications of these changes is often not carefully considered. Surface finishers then try to adapt the process to their site-specific requirements. Changes may be incorporated, whether to chemistry or equipment, that do not look beyond the immediate process. The danger is that unconsidered relationships can wreak havoc on process changes. It is crucial for incorporating pollution prevention goals and reduced exposure that process evolution be controlled through a stepwise fashion. The goal is to define a pathway leading to the most efficient, cost-effective, and safest production of high-quality products. This statement can be used to define evolution: Because each item is a moving target, the evolution of a process does not define the endpoint—only the pathway. This definition is consistent with total quality approaches and the tools used in evolving quality programs are directly applicable to process improvement.[2,5]

Process Analysis

A complete analysis of a process change may appear to be overwhelming when you consider all the potential repercussions of even a minor change. Once the analysis is begun, however, many sources of information and data will become available that will effectively shorten the process. Fully understanding “flow” in the facility, as well as factors outside of the immediate area that can affect the process at hand, provides the necessary data to determine the real magnitude of the proposed change. This information comes from establishing strong communication between the other process areas, facilities, environmental, health and safety department, and engineering and design functions. Analyses are best completed by a team approach, where input on the potential consequences to all aspects of the business may be solicited.

A Case History

Consider a chemical conversion coating line where product quality is checked by regular humidity tests. The machine shop has changed cutting fluids that are not cleaned adequately by the current pretreatment. In this example, if the process is treated as a stand-alone line, the failed humidity tests would likely result in testing the baths, which may or may not show abnormally high-soils loading. Test failures of a key process threaten product shipments; consequently manufacturing engineers from the machine shop are included in the problem-solving efforts. Finally, the change in the cutting fluids is revealed.

Utilizing the team approach to review all process changes clearly would have short-circuited the above example. The plating supervisor, who is involved in the review of the cutting fluid change, asks to test-clean a few parts machined with new cutting fluid, and discovers that to adequately clean the parts, the cleaner concentration must be increased by 50 percent. This causes the plating supervisor to consider a separate preclean tank for these parts because the higher cleaner concentration could affect other parts processes through the plating department. As a corollary, the environmental department asks if there will be any impact on the sludge generated by the waste treatment system as a result of the change in cleaner loading. Understanding the process in a global sense, as well as in detail, makes the analysis of change a manageable task.

Process analysis can be carried out without a team of analysts. This requires, however, a greater degree of understanding of the entire facility and product flow. A key element necessary for process analysis is establishing detailed procedures to control all in-house processes. Operating procedures detail the process steps and the key parameters that are monitored to insure proper functioning. These procedures need to be well established and followed, to instill trust and repeatability in the process. Charting of key parameters is a simple way to track process health. Procedures can also be used as a repository of the evolutionary history of the process by indicating the type and reason for past changes. Full process understanding includes the ability to demonstrate control by measuring the key indicators. Statistical process control (SPC) tools and techniques are used to accomplish this task efficiently.[5,6] SPC techniques, properly applied, can provide critical information on process variation.

Understanding critical variables and controlling these factors establishes the operational limits of the process. It is necessary, however, to remember the limitations of statistical tools. Disproportionate information is collected while a process is being proved out, and once consistent quality is attained, testing becomes less frequent. The level of testing then is generally no more than the bare minimum to insure the standard of quality. This amount of testing is generally insufficient to evaluate the impact of process changes in the short term.

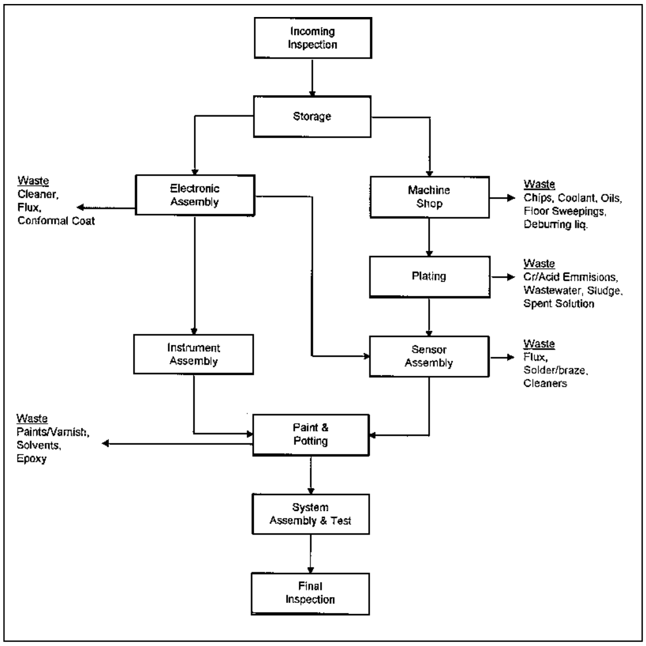

Fig. 1—Facility process flow diagram.

An understanding of facility-wide process flow can be gained by constructing flow charts. The flow charts can be extremely detailed, depending on the complexity of the facility. Tiering these diagrams to finer levels of detail (the most detailed being the process work instructions) provides an easy method of simplifying product flow in a complex facility. Figure 1 shows a simplified facility flow diagram. It indicates the production flow and shows the general pathway for product and wastes produced by the facility. Areas of impact from contemplated changes can easily be identified from the general diagram. Refinement of the general process diagram leads to more detailed ones for the various process task areas.

Figure 2 depicts this type of detailed diagram for plating process flow. These tools can provide a relatively simple means to identify the areas where process change can drive changes in other processes. When control and procedures have been established for a process, data can be collected on the various inputs and outputs. This information is used in defining process limitations and uncovering opportunities for optimization. Setting goals and defining expected outcomes for process evolution is perhaps the most difficult task. Process evolution is most effective when done in a step-wise approach, often involving parallel paths. Simple steps that make modest gains with little cost serve to instill confidence that orderly change can occur, providing the fuel necessary for selling major costly changes.

Understand the Process

Cyanide is historically one of the most important and versatile ions in surface finishing. Environmental, health, and safety constraints have placed enormous pressures on its use, and sparked a wealth of activity to develop non-cyanide alternatives[7–11] for almost all applications. Generally, the non-cyanide processes are less robust and less versatile. In addition, these replacement proprietary processes may not be provided with sufficiently in-depth technical data to effectively and truly control them.

The first step in pollution prevention and for process analysis is to completely understand the process. A switch to a process that does not perform the same as cyanide just to meet pollution prevention and source reduction goals is not necessarily the prudent step. Cyanide-based processes may have a poor reputation, but they are well understood. Most cyanide-based processes may be operated on a closed, or nearly closed-loop basis.

Evaporative recovery, ion exchange, electrowinning, and reverse osmosis have all been utilized

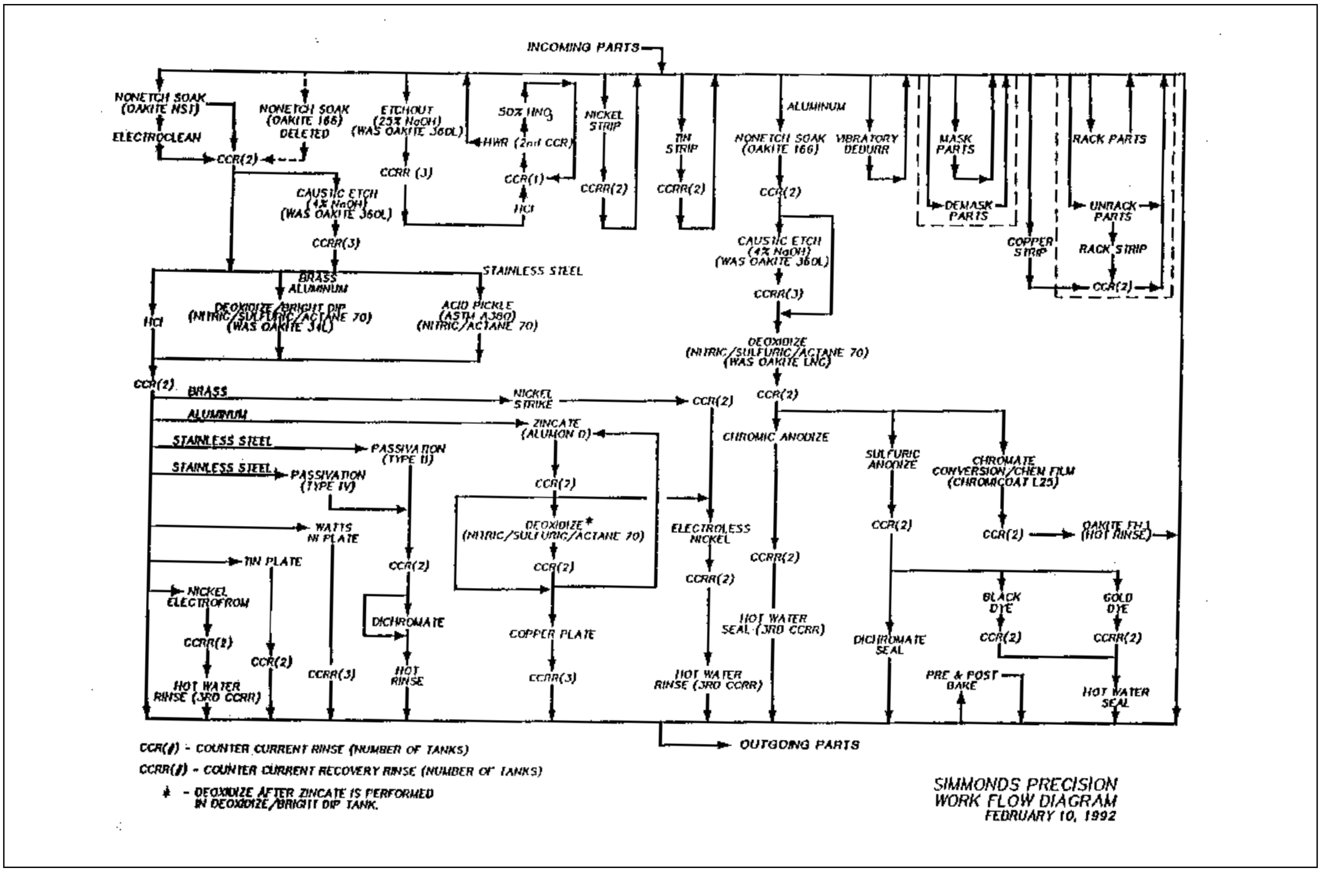

Fig. 2—Plating process flow.

effectively to manage cyanide processes at the source.[12–15] Cyanide is an extremely toxic chemical[16] and is an undeniable potential hazard in surface finishing facilities. Other common surface finishing chemicals, however, have lower exposure thresholds and are not treated as severely, because they do not carry the same emotional baggage. Hazardous processes require especially good housekeeping practices to complement these technologies.[17,18] The question is: Can this hazard be sufficiently minimized and controlled so that process engineers may select processes, non-cyanide or cyanide based, which yield the greatest advantage? Based on the above discussion, cyanide may be more properly defined as a health and safety problem.

Controlled Evolution Of a Process—Background

An aerospace company manufactures thousands of printed circuit board (PCB) assemblies to support its production needs. The empty PCBs are purchased out of house, hand assembled with purchased electronic components, wave soldered, defluxed or cleaned, tested, and urethane-coated prior to use in an assortment of products. The overriding process parameters were driven from soldering specifications required by customers, which originated primarily from military specifications, such as Mil-P-28809 and Mil-STD-275. From about 1970 until 1988, the circuit board assembly process remained largely unchanged, except for the fact that the boards became more densely populated and the designs more complex. Many factors influenced the business to cause it to look at improving this process, including a major government supplier quality assurance audit, down-turns in the aerospace market, changes in business philosophy on stocking raw materials and parts, and increased sensitivity to emission of volatile organic compounds. In looking for ways to reduce cost and improve quality, several process factors became apparent: The PCB assembly process was labor-intensive, quality was maintained only through extensive rework and solder joint touch-up, cost and availability associated with traditional cleaning solvents were changing dramatically, and waste emissions (both air and off-site disposal) were becoming significant issues. Process improvements aimed at solving these problems would require extensive changes, which would affect all aspects of this process from raw material purchasing to end item customer contract specifications. The interrelationship of these process parameters required careful consideration of the many potential changes to be tackled. Some, by necessity, were addressed along parallel paths. Analysis of the various alternatives led to a step wise approach where simple improvements were made immediately, while investigation of the more costly and/or politically more difficult changes was performed. The process improvement goals included:

1. Improved first-time yields (reduced rework)
2. Reduced labor costs per board
3. Reduced environmental impact
4. No loss to production schedules during implementation

Pathway for Process Evolution

Developing a strategy to achieve these goals was a difficult task because of the interrelationships of the areas affected. Significant changes to the PCB assembly process could put production requirements and schedules at risk, as well as the more serious implication of process errors affecting long-term product reliability. A key driver in this process was the age of the components stocked. Long-termed parts stocking led to rework because exposure of tinned surfaces encouraged oxidation. This led to degraded solderability, additional cleaning steps, and additional inspections.

The relationships of the many manufacturing and support functions would not allow single, independent changes. For example, the elimination of the solder dip operation resulted in multiple effects, each requiring action from various functions, including purchasing, contracts, incoming inspection, and manufacturing. The absence of fresh tin on the component leads required improved control of inventory stock, because age of components adversely affects solderability. Environmental regulation was also pressing for the removal of chlorinated solvents more quickly than originally projected. Examination of each of these facets of the process revealed significant areas for improvement. Each change required review and approval by all departments, as well as by customer representatives. Company-wide modification of process procedures improved documentation of existing procedures, and revisions triggered appropriate review of affected departments. New stock room controls were implemented to insure that "first-in, first-out" stock turnover was practiced, and to reduce inventories. Receiving inspection was required to achieve 100 percent acceptance of parts by qualifying vendors to prevent part shortages, or acceptance of off-spec parts to avoid missed shipments. Process quality measurements were instituted with SPC principles[6] to improve first-pass production yield. Improved procedures and SPC provided the data necessary to investigate extraneous operations. Taguchi experiments were constructed to establish stock room holding limits and maintain the solderability of stocked parts. Intermediate steps with low-cost gains were identified, while long-term solutions were investigated. Cleaning methods were examined and new methods considered to replace the CFCs slated for elimination. The phaseout originally planned for 2005 was moved forward to 1993. Therefore, testing schedules for approval of cleaners and equipment were accelerated.

Communication

The issues surrounding these goals were extremely complex, affecting all levels of the organization and including interactions with vendors and customers. Little communication between affected departments existed up until this point. A major business reorganization took place at the company. Total quality approaches were adopted and process teams were established, including design engineers, purchasing representatives, production, and quality personnel. Formation of the teams created common goals, open communication and knowledge sharing. Ideas never before considered were now openly discussed.

Also during this same time, many customers, including the military, realized a serious need to change their outdated specifications. These changes departed from process-specific specifications to results-oriented. For example, previously suppliers were required to use only chlorinated solvents or blends for cleaning and defluxing assembled circuit boards. The specifications now allowed substitute processes that could demonstrate certain minimum levels of cleanliness. More emphasis was being placed on qualified vendors supplying guaranteed quality parts. Receiving inspection began to utilize new technologies in measuring solderability of purchased parts.

Process Control

True process control was not measured by first-pass yield. At one time, this process was measured by how many solder joints passed visual inspection after rework! In other words, the process accepted rework as a normal part of the assembly process. In order to effectively evaluate any changes, an understanding of the process capability is required. Extensive work was required to install accurate value-added process measurements that would provide data on actual capability. These measurements served as a ruler to judge process changes. Taguchi techniques for evaluation of process variables and their effect were utilized. Process quality variables were identified and those having the largest effect were studied.

Another key part in communicating information about this and other processes was maintaining high-quality procedures. A great deal of effort was put into formalizing the practices used to make the end items on the production floor. Audits against the procedures were also improved and the audits were used to identify areas where practice differed from procedure, and often identified errors in written procedures. The procedures also carried a revision history that allowed persons unfamiliar with the process to track its evolution and avoid repeating past mistakes. Review of potential changes was also incorporated to evaluate the impact both to the current area and the outside areas affected by the change. Material tracking was improved to accommodate the need to reduce inventories of stock parts to their lowest practical levels. This had the added benefit of providing more accurate data to determine balances of raw material used and wastes generated. Tools could then be created to track these items. The changes benefited the entire business and significantly reduced the wastes generated.

Process Changes

Contamination

Soldering quality is directly related to the solderability of the components and PCB to which they are soldered. Many factors can affect solderability, including component quality, which is dependent on the suppliers, and in-house contamination of these components. The component in-house contamination seen during the course of this project originated from several sources. Silicones used in this and other adjacent processes migrated onto the components and PCBs. These soils were not effectively removed by cleaning or the action of the fluxes. All possible sources of silicone were, therefore, eliminated. Changes resulting in the use of finger cots, gloves, new hand lotions and washroom soaps were incorporated. Storage bags and containers used to store components between intermediate processing steps were reviewed and changed. Duplicate cleaning steps between manufacturing operations were eliminated.

Receiving inspection began to utilize new technologies in measuring solderability of purchased parts. A meniscigraph was purchased to allow a quantitative measurement of solderability of all purchased components. Vendors were held accountable for poor quality, and purchasing agents worked to keep the assembly line stocked with compliant parts. Before purchase of this device, all components were tin-dipped prior to assembly to assure soldering quality. By putting the responsibility of solderability onto the supplier, and having the capability of quantitatively assuring a minimum level of quality, this operation, accounting for more than 15 percent of the total labor in PCB assembly, was eliminated. With the reduction of labor came materials savings and reduction in waste and emission of about the same percentages.

Solvent cleaning

Elimination of ozone-depleting chemicals was a major process improvement that significantly reduced costs and environmental impact. Until about 1988, 1,1,1-trichloroethane and freon 113 were the primary cleaning solvents used to clean components and finished assemblies. This cleaning was accomplished using two methods—vapor degreasing and bench-top, cold-hand cleaning. As the costs of virgin solvent began to increase, and reporting on the Toxic Release Inventory raised public awareness, the use of the solvent was studied. The first step reduced the number of operating vapor degreasers. The quantity of solvent allocated to each bench was limited (1 pt vs. 1 qt) and leftover solvent was collected at the end of the shift. The waste material was reprocessed, and on-site recycling further reduced the use of virgin material. Finally, improvements in the operating efficiency of vapor degreasers to reduce solvent losses were explored. Employees were included in the solvent reduction program and encouraged to share solvent cans, keep lids closed, and offer suggestions on eliminating cleaning steps.

The printed circuit board soldering operation was supported by an in-line, vapor cleaning unit that was used to clean boards prior to, and following, wave solder operations. The machine used freon for cleaning and was also designed to accept HCFC replacement cleaners. The accelerated phaseout of chlorinated cleaning materials required the abandonment of this equipment after only five years of its projected 15-year lifetime. Extensive testing of terpene-based materials proved very positive and gained customer and military approval as a substitute for the vapor cleaner. This change dramatically reduced the use of chlorinated solvents, the associated air emissions, and waste generation. The final step came in 1993 when isopropyl alcohol was substituted for the remaining chlorinated solvents in bench-top hand-cleaning, allowing the company to avoid the labeling requirements by being CFC-free.

Wave Solder

The most recent change in the evolution of the PCB assembly process occurred in 1994 with the installation of a new oil-free, wave solder machine. This machine eliminated another relatively large waste stream at the plant. The machine also provides greater flexibility and improved performance. It is particularly well-suited to the highly populated PCBs routinely processed. In addition to the waste reductions, the use of flux is reduced, as are air emissions.

Goal Attainment & New Goals

The PCB assembly process is very different from what it was in mid-1980s. In addition to the successes described here, the process is now covered by Mil STD-2000 Rev A. This specification is more results-oriented and affords greater flexibility in producing the necessary quality by allowing for the qualification of alternate processes. Evolution of this process has not stopped. Current projects are looking at various aspects of the process. Improving vendor qualification and verification are being investigated. Efforts to reduce isopropyl alcohol, the main solvent used, are progressing, as well as efforts to minimize flux usage. Currently boards must pass through the wave solder operation multiple times as they are built up with components. Efforts are being made to develop designs that will accommodate single-pass soldering of the PCBs.

Control & Adapt For the Future

Controlling change is key to optimizing processes, particularly when the mandates required by pollution prevention and waste minimization are to be effectively addressed. Successful programs follow along the same paths as total quality programs, applying many of the same principles. Interfunctional teams are generally used and options are rarely discarded, but are acted on or catalogued for future consideration. There is no one formula for success. It is certain, however, that the formula will change as new information is uncovered. Adapting to these changes and establishing new goals to replace the old ones is crucial for keeping the process moving forward. Optimizing a process, whether for pollution prevention or any other reason, is evolutionary, not revolutionary, and thorough process analysis can be accomplished in an analytically sound manner. ***P&SF***

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