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Abstract
Selective soldering is now an extremely popular methodology for joining through-hole components to PCBs. After its inception in the 1990s, it has established itself as a mainstay production technique for printed circuit board manufacture in both hand-load machines and in-line conveyorized systems.

Challenges in selective soldering generally can be attributed to either process requirements such as process speed or complexity of design requiring changes in soldering parameters to achieve good quality. This paper analyses the key process steps and parameters to achieve an optimal selective soldering process.

Typical steps in a selective soldering process are fluxing, preheating and finally soldering. There are many variables and different technologies that can be employed in each of these processes that build into a complete soldering process. By analyzing the variables, technologies and challenging factors in selective soldering, this paper will present a methodological consideration on how to minimize errors and increase soldering quality.

Selective soldering has now reached a stage of maturity where it can be considered its own processing technology distinct from but still bearing similarly to wave soldering. As such, PCBs should be designed with this processing technology in mind.

Designation of through-hole areas late into design can lead to the implementation of difficult-to-achieve selective soldering. This can result from closeness to surface mount components or cycle time pressures due to lack of understanding of the selective soldering method.

A full consideration of PCB design, component choice and manufacturing steps is essential for efficient and optimal selective soldering of through-hole components.

Keywords: Selective soldering, Design for manufacture, Process engineering

Introduction
Selective soldering typically utilizes a wettable nozzle to deposit solder onto the leads or pins of through-hole components. This connective technology saw its inception in the 1990s and has now grown in popularity to be a mainstay of electronics production.

With the adoption of surface mount technologies, it was thought, for a time, that selective soldering would become less popular however with the adoption of electric vehicles and the increased requirements in the telecommunications fields, this has not been the case. Furthermore, the aerospace and defense fields, medical fields and power delivery sector are continuing to favor the selective soldering methodology.

At first, the selective methodology was an offshoot of wave soldering. This is evident by the adoption of similar design and processing methodologies. Examples include angled conveyors with the purpose of debridging joints or the specific use of debridging tools. In soldering technology-specific books, selective soldering can be seen as referred to as “selective wave” [1] or omitted entirely [2]. Academic articles will also group the two technologies together [3].

For simple PCB designs, those that lack large capacitors or connectors on the soldering side, wave soldering may be the simpler process to use. Boards such as this may require some masking but otherwise, they can be soldered without difficulty. Overall efficiency of the process is another matter. As wave soldering utilizing a larger solder bath, it requires more power to keep the solder molten overall. Additionally, the reduced inertion efficiency and the turbulence of the solder waves will lead to a larger amount of dross generation. As a result, more solder is wasted in a wave soldering process.

Miniaturized wave soldering apparatuses are present in selective soldering and can be used to target simpler pin layouts i.e., those lacking components around them.

As well as the wetted solder apparatus, non-wetting dip nozzles are used [4,5]. For higher volume, low complexity products, the use of nozzles such as these can be an excellent option to increase the throughput of finished PCBs. There are several downsides to this type of assembly such as the lack of per joint customization of soldering parameters. As a result, rework may be required for certain joints as process changes cannot be made to improve the soldering quality without affecting all the joints soldered by the dip nozzle. Additionally, the assembly in the solder bath must often be customized to accommodate this nozzle type meaning that should a user wish to switch to wettable nozzles or a wave assembly, it may be more efficient to have a bath customized for certain types of soldering apparatus. Additionally, if any design changes are made, a new dip nozzle shape will be required. If the soldering layout is unique to each board, then a different shape of dip nozzle will be needed per board.

Types of challenges in selective soldering

Before classifying the challenges in selective soldering, a review of the elements in a full selective soldering process is essential. The general procedure is as follows [1]:

- Fluxing
- Pre-heat
- Soldering

The use of pre-heat is not always necessary as boards vary in their thermal load requirements depending on thickness, ground planes and component selection. Furthermore, the flow of solder through a nozzle applies heat to the board as contact with the solder allows for thermal conduction.

Process Challenges

Fluxing fulfils several purposes for the selective soldering process:

- Creating a film between the solder mask and the solder to avoid the adherence of solder to the PCB.
- Cleaning the metal surfaces of components to remove oxides to make soldering possible.
- Promotes the wetting of the solder for better hole fill.
- Aids in the prevention of solder bridges and solder balls.

There is no one size fits all flux; they can be low-solids/no-clean, high solids containing rosins or water soluble [6]. Low solids/no-clean fluxes can further be broken down into alcohol-based (rosin or resin containing), alcohol-based (rosin or resin free) and water-based (generally rosin or resin free). Solid content can vary as can the active chemistry. Application methods can vary depending upon the process requirements but generally, two methods are used. The drop-jet can quickly apply miniature droplets in a precise fashion. Water and alcohol-based fluxes can be used with the drop-jet. When a larger area is to be soldered, an ultrasonic head generally is used. This fluxing module is lower maintenance and can handle higher solids content fluxes.

Groves and Wol [6] reviewed the various types of fluxes for selective soldering as well as their advantages and disadvantages. For selective soldering, low-solids/no-clean flux with low rosin content is preferred as they offer a wider process window and are more successful with a wider variety of products and programs requiring a range of heat or time at elevated temperatures.

After fluxing, the board would generally be pre-heated. This activates the chemistry of the flux and prepares the board to better wet the applied solder. Most commonly, infrared (IR) lamps are used with a wavelength between 750 nm and 3000 nm. Balancing the wavelength of the IR with the absorption of heat of the parts is key. IR can quickly respond (1-3 seconds) to heat the board and can be used in a closed loop mode (taking a temperature reading and altering the power to hit a desired thermal profile) or an open loop (where the lamps simply heat the assembly without imposed power control).

For thicker boards, convection heating may be used. This technology is slower to respond than IR resulting in pre-heating steps in the range of multiple minutes compared to 1-2 minutes for IR. Convection is, however, able to evenly heat thicker PCBs and isn't bound by the reflectivity issue of different wavelengths of IR lamps.

To achieve the optimal pre-heating for a specific product, a thermal profiler should be used to determine the maximum temperature, thermal ramp rate and pre-heating time. For some processes, the PCB is then enough that pre-heating doesn't need to be used and the heating from the applied solder is enough. The order of fluxing and pre-heating can be changed depending on the process requirements for the board and depending upon the flux being used. As heating is applied to the board, a water-based flux will spread whereas an alcohol-based flux will begin to evaporate. Proper process engineering ensures that the order and timings of these processes are specified.

Following these steps, it's finally time for soldering. As with all the other elements of the selective process, there are multiple parameters and options to consider during this step:

- Inertion: To maintain good flow characteristics and reduce the amount of bridging, a low-oxygen environment is used. Nitrogen is typically used for inertion to achieve sub 10 ppm of oxygen. 50 ppm of oxygen is the maximum permissible limit, above this the solder quality is affected and dross is generated at a higher rate.
- Positioning of the solder bath/nozzle: The bath positioning can be used to either apply soldering to a single joint or closely packed series of joints in a dip step or movement along the underside of a PCB. The machine can be programmed for rows of connectors as part of a draw step.
- Contact time of solder: Greater contact time can aid wetting and pull-through of solder but increasing the time can dissolve copper from the PCB.
- Type of solder: lead-free or leaded; inclusion of additives to alter the liquid properties or the mechanical properties of the solidified joint.
- Use of wetting or non-wetting nozzles: non-wetting dip nozzles can be used for fast production of high-volume products, but they lose the per-joint customization of a wetting nozzle.
- Top-side heating during soldering: used if the assembly has a high thermal mass that required continuous heating to ensure good solder pull-through.
- Solder temperature: The soldering temperature is chosen to balance good pull-through, flux activation loss and increased likelihood of oxidation. Generally, the temperature will be in the range of 280-320 °C.
- Board warp correction: the application of heat to the PCB can warp it enough to affect the soldering process. The use of a laser positioning sensor can apply live offsets to the programmed height to achieve good soldering.

Nozzle size and type can be customized for specific joints (through the use of multiple soldering stations), but the correct programming must still be utilized as there are so many parameters that interact to produce a well-soldered joint. With new materials engineering, the maintenance can be reduced as surface engineered soldering nozzles [5,7]. The increased wetting enabled by surface engineering technologies allows for faster startup of the nozzles, easier rewetting and less dewetting during process. Cleaning is still essential to keep a nozzle running well no matter the material design[1].

A unique item that poses a challenge is not, in fact, an issue of process technology but is more people centered. No one likes doing maintenance, but it is essential to keep all machines working properly. Machine wear out is inevitable. Proactive maintenance is undoubtedly better for a full production environment but this this requires an initial time investment to establish the required systems [8]. This will be covered in more detail later in the article.

Sometimes nozzle sizes are chosen to fulfil the requirements of multiple products. In this case, it is often more optimal to use planned machine downtime to swap to a different nozzle size to produce better soldering quality. This takes more time and planning from maintenance staff, however. Some users may use heated bath trolleys to allow for faster changing of baths (to use different solders or a different nozzle geometry). The heating function also allows maintenance to be carried out on the baths outside of the soldering system; when the bath cools the impeller chamber is frozen, so it is inaccessible.

Finally, electronics manufacturing is becoming increasingly automated, and the soldering systems must be adapted to fully integrate with this new paradigm of manufacturing. Examples include the use of robot arms to load PCBs into the machines, resoldering in in-line soldering machines based on optical inspection results and automated nozzle conditioning and solder top-up systems.

Nozzle size choice is a complex issue in itself. In general, it is best to choose the largest nozzle possible as this gives fewer flow and heating issues. In fact, larger can help with heat transfer due to the larger amount of solder flowing through the nozzle. We can define the nozzle diameter to hole diameter ratio as:

$$R_s = \frac{D_n}{D_h} \tag{1}$$

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[1] Nozzles are also cleaned with flux however a different chemistry is utilized to remove the oxides that form on the surface of the ferrous materials utilized as nozzles.

Where D_n is the diameter of the nozzle and D_h is the diameter of the through hole on the PCB. Generally, this ratio would not be less than one as if we were to perform a dip step, we would not be able to fit the lead inside the nozzle barrel. This does not pose an issue if the nozzle is larger but then we must think about the projected spot size of the solder flow on the board and consider whether this will interfere with any nearby components. Additionally, small clearances are beneficial as this reduces the time for the solder bath to move the soldering nozzle into position.

Design of a selective soldering line can be a challenge in itself as often the cycle time requirements may be set without reference to realistic processing times for selective soldering or may be in reference to previously used wave soldering equipment. Table 1 shows an example sequence of a selective soldering process where, with each optimization step, the aim is to reduce the total process time. In this example pre-heat time is fixed are we are assuming that it is operating with fixed time in open loop but this is not indicative of all processes; the pre-heat time could be reduced by using a closed loop system and heating to a desired temperature.

A basic process may start with fluxing, preheating and soldering (with one bath) as separate steps. As soldering time is generally the main constraining factor, that is generally where the first changes are made. For the first step, the soldering module may instead be equipped with 2 baths allowing for the grouping of joints to each bath thereby reducing overall soldering time. The movement time of the soldering bath is reduced resulting in a reduction of the time for this step. At the next optimization step, a different configuration may be used where the soldering modules contain top-mounted pre-heaters allowing the pre-heating and soldering to take place within one machine frame with the two processes occurring concurrently.

There are many other options that are available, but this gives some insight into the process engineering that occurs in the specification of a selective soldering line. Transfer time consists of using the conveyor to move boards, solder bath level checking, fiducial measurements and adjustments, nozzle wave height adjustment and nozzle conditioning. The total time consists of 10 seconds each for initially bringing the boards into the machine, moving between the various functional stations and then a shorter transfer to the next machine in the line once the selective soldering operations are complete (5 secs). These processes are standard across all selective soldering manufacturers. Note that these times and steps are not in reference to any specific process and are simply representative values.

Table 1. Example process optimization steps for a selective soldering process.

		Process step and time (secs)				
Level of optimization	Process notes	Fluxing	Pre-heating	Soldering	Transfers	Total
Initial	Fluxing, preheating and soldering as separate steps.	15	60	60	35 (10+10+10+5)	170
First step	Fluxing and preheating as separate steps. Soldering step uses 2 solder baths within one machine.	15	60	30 (15+15)	35 (10+10+10+5)	140
Second step	Fluxing as a separate step. Preheating using integrated system in soldering machines.	15	60	30 (15+15). In parallel with pre-heating.	35 (10+10+10+5)	110

Board-specific challenges

Often process engineers will encounter PCBs where little consideration has been given to the end manufacturing process. As selective soldering will be viewed as the last element of the manufacturing chain, it is the last thing a design team may think about. Furthermore, many design teams may not be experienced with optimal design elements to enable fast processing with selective soldering. Often extended nozzles need to be used to work around tall components. Additionally, boards that were built with surface mount technology (SMT) assembly in mind may require some element of selective soldering thereby necessitating the use of smaller nozzles with more precise programming. An example of this close surface mount that may occur on a PCB is shown in Figure 1.

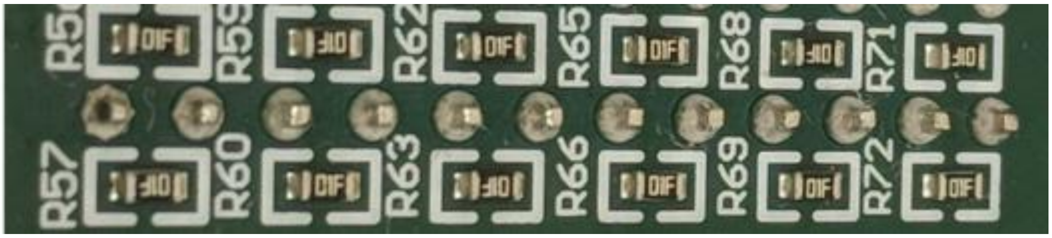

Figure 1. Selective soldering training board showing close proximity of surface mount components to through hole soldering areas.

Improved selective soldering technology does allow for soldering close to SMT and around metallized areas. Using small diameter nozzles (as shown in Figure 2), with small projected solder spot size on the board, gives the capability to solder close to SMT and within metalized areas.

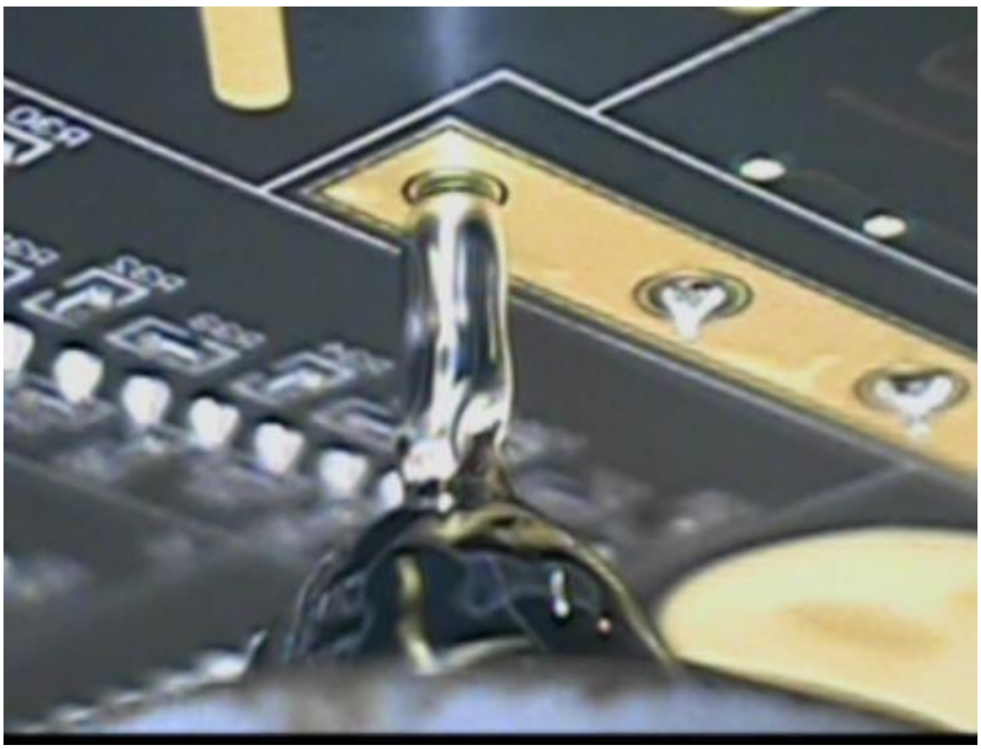

Figure 2. Small diameter nozzle soldering within the tight clearance of a metallized zone.

Smaller nozzles such as those in Figure 2 will wear out faster than a larger nozzle as the wall thickness is smaller and the wear rate with a lower mass nozzle will cause them to fail faster. However, it should be noted that due to the nature of the wetting reaction, wear is always present on wetted selective soldering nozzles [4,5]. Certain process steps can be taken to extend the lifetime such as alternating the direction of draw steps to ensure even wear on the trailing and leading sides and using a pump speed burst to quickly rewet the nozzle after a long operation. These parts remain sacrificial however and all programmed processes should be to primarily maximize the soldering quality and not to extend the lifetime of the nozzle.

With the rapid increase in electric vehicle systems, there has been an increase in PCBs bonded to larger cooling assemblies which pose a challenge in terms of pre-heat as well as soldering larger components such as insulated-gate bipolar transistors (IGBTs). These board-specific challenges require careful setting of process parameters to ensure good soldering within the time requirements. This involves setting the pump speed to achieve the correct level of solder fill and ensuring the nozzle remains wetted, programming the optimal vectoring of the solder bath and pull-off characteristics to reduce bridging.

When creating a selective soldering process, the same constraints apply as in project management. The engineer must balance the competing forces of quality, cost and speed. This is shown in Figure 3. Generally, two of the main constraints are chosen to the detriment of the third but some allowances can be made with optimal design.

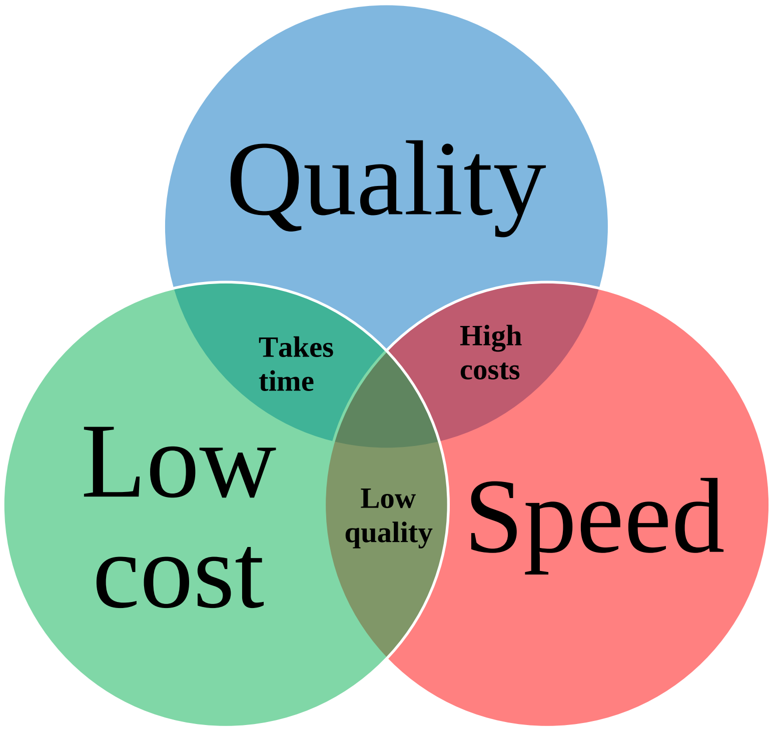

Figure 3. Venn diagram showing the Triple Constraint symbolizing weighing opposing forces in a project.

One method to improve overall speed is the integration of design for manufacture (DFM) [9–11] and design for assembly (DFA) [12]. Stoll [9] reviewed some of the fundamental principles of DFM with examples such as minimizing the total number of parts, developing modular designs, designing parts for multi-use where possible, using standard parts and developing parts for ease of fabrication. Complexity in engineering arises from a number of factors such as product structure, manufacturing technology choice, customer requirements and planning and scheduling [11]. By focusing on controllable elements such as the design, number of parts and number of fasteners or the assembly method [12], the complexity can be reduced thereby decreasing cost and increase speed of manufacturing.

Design for manufacture considerations have been present in the electronics industry for a number of years. As an example, DFM was utilized by a semiconductor chip manufacturer for faster production of 45 nm chips in 2008 [13]. For selective soldering, efficient assembly can be achieved by utilizing the maximum PCB size accepted by the machine in use. For smaller boards this may therefore require the use of carriers or larger master panels so multiple boards can be held in the machine for soldering. The PCB carriers utilized for this can be manufactured in such a way as to only allow installation of a PCB into a carrier one way thereby speeding up handling speed.

Training in selective soldering processing

Many manufacturers begin using selective soldering after having wave soldering equipment. Broadly the two pieces of equipment perform the same role, however the number of parameters that can be altered in selective soldering are far greater. Generally, in wave soldering only the wave height, temperature of the solder and conveyor speed will be changed.

As a result, greater training is required through industry to disseminate specialized techniques that can be applied in selective, identify the differences between different solder types and how they respond to the selective process, identify defects and parametric methods to address them and finally design for manufacture considerations for selective soldering (i.e. placement considerations for tall components and surface mount components) [14].

Training boards such as the one in Figure 4 are an excellent training tool as they feature multiple sections for different training requirements. The red highlighted areas are for solder practice using a small diameter nozzle allowing you to solder near metallized areas or SMT components. The blue area is to test the effectiveness of fluxes for solder spreading; the cross pattern is used to highlight the spreading further. The yellow area is to test the wetting performance of flux on a bare metal finish. A solder draw can be programmed on this area to observe solder wetting and spreading. Finally, the green area is used to observe flux wetting on solder mask.

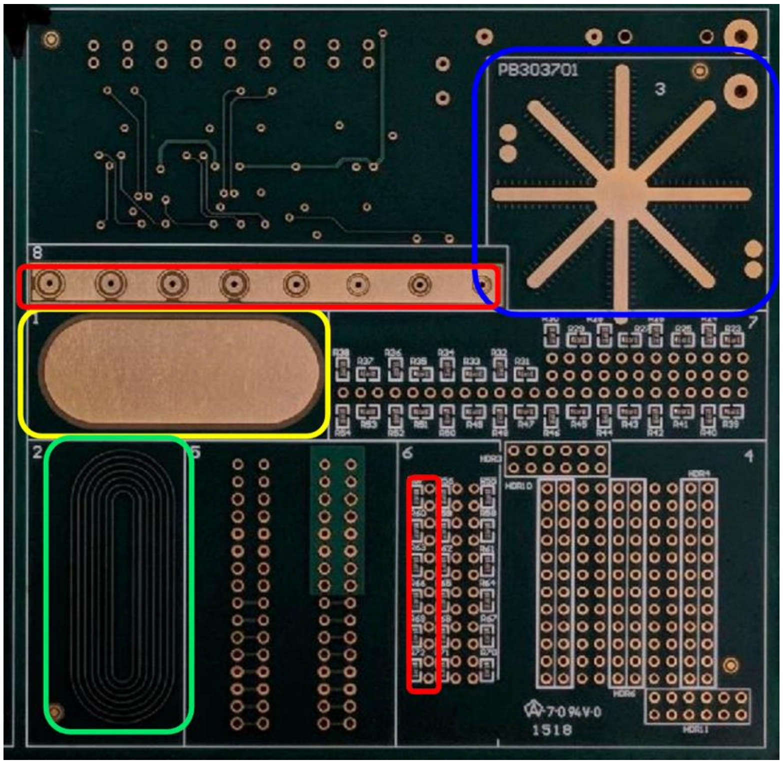

Figure 4. Example of a selective soldering training board.

Maintenance

Maintenance is an inevitability in all systems, and this is not unique for selective soldering systems. The mechanical systems require regular cleaning, lubrication and checking for excess wear indicating that the part is about to wear out. The solder baths themselves require maintenance and as such it is a priority to ensure that they are free of debris and dross, as this can affect the soldering quality. The use of inerting nitrogen systems functions to blanket the bath and inert the area around the nozzle to improve wetting of the solder to the nozzle and reduce dross generation. Note that the generation of dross will occur even with excellent inertion (<10 ppm of oxygen measured above the nozzle) as elevated temperatures speeds up the oxidation process.

Many of the selective soldering platform suppliers favor the electromagnetic bath which does away with the impeller and instead uses electromagnetic pulses to drive solder through the system. Of course, these systems do not require maintenance of an impeller but that does not negate the need for maintenance. The presence of an inertion system will slow down dross generation but it cannot be completely eliminated. Dross must be removed from all solder pumps as its presence can affect solder flow through the nozzle assembly due to the potential of blockage in extreme scenarios.

Dross primarily consists of metallic oxides as shown in the x-ray diffraction (XRD) in Figure 5. XRD can be used to observe both single crystals and multi-crystalline materials, it allows for the characterization of materials based on their diffraction pattern. X-rays are scattered from an x-ray tube and reflected through the sample and onto the detector across a wide angular range. At points corresponding on atomic spacing, the x-rays constructively interfere and by analyzing these angles the atomic spacings can be determined. This can then be cross-referenced with databases to identify a material [15] . As oxides are generally harder than most metals [16], these small particulates could act in an erosive manner when circulating in the pump system.

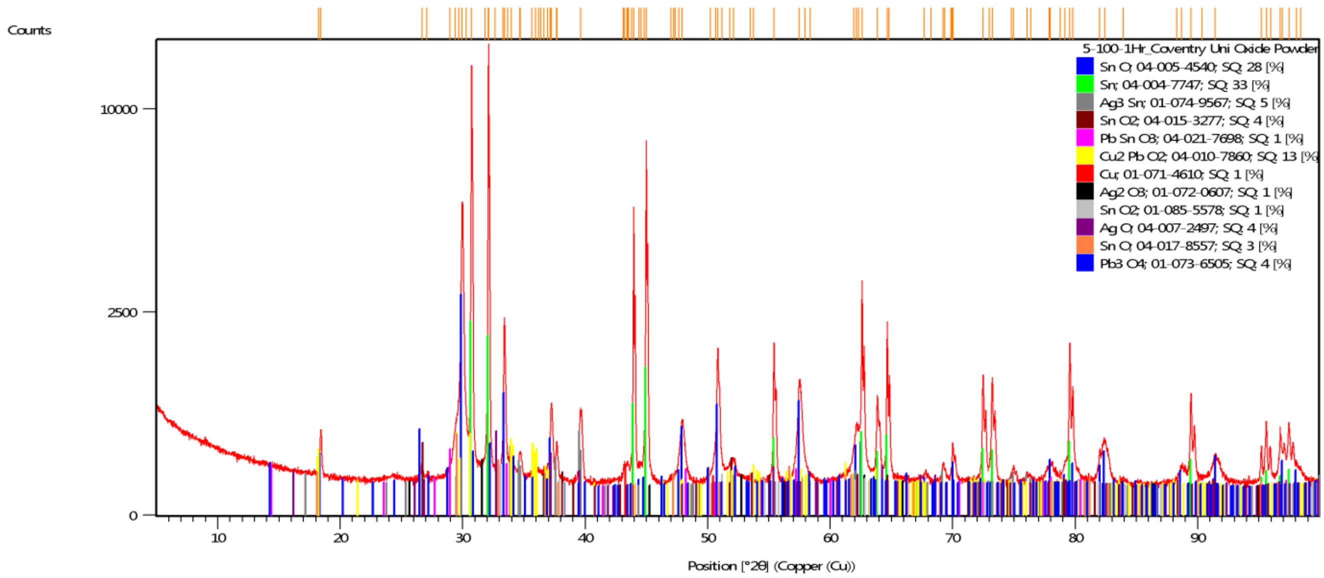

Figure 5. XRD spectra of a sample of dross extracted from a SAC305 selective soldering bath.

The soldering bath that this sample was extracted from was utilized to test the effectiveness of inertion systems Leaded solder was used initially before being changed to SAC305 later. The phases that were identified are shown in Table 2.

Table 2. Identified elements and compounds and composition from XRD scan in Figure 5.

Type of material/compound	Phase identified	Chemical formula	Composition (%)
Metal	Tin	Sn	33
	Copper	Cu	1
Metallic oxide	Tin (II) oxide	SnO	31
	Tin (IV) oxide	SnO_2	5
	Copper lead oxide	Cu_2PbO_2	13
	Silver (I) oxide	AgO	4
	Silver (III) oxide	Ag_2O_3	1
	Lead (II, IV) Oxide	Pb_3O_4	4
	Lead tin oxide	$PbSnO_3$	1
Intermetallic	Silver tin	Ag_3Sn	5

As we can see from the table, the composition of dross can become complex with multiple oxides of different elements, compound oxides and even intermetallics. The formation site and mechanism of the intermetallic formation in the dross is unknown at current; generally, they are formed within the solder joint itself and play a part in controlling the microstructure and physical and mechanical properties of the solder joint. Excessive thickness of intermetallics are well known to lead to failures [17–19]. It is interesting to note that lead is present in the bath despite the solder being lead-free SAC305. This is likely due to leaded solder previously being in the bath and its contaminant presence was detected. This is of interest to show that leaded solder baths cannot easily be converted into lead-free baths.

It is a common question to ask when acquiring a new piece of equipment; how much maintenance must be performed and how often? Some may be disappointed to learn that their new acquisition is not maintenance free; no mechanical system is. It is this attitude to maintenance that treats it as purely reactive thereby resulting in downtime and increased cost [20]. Instead, engineers and operators should seek to move from a reactive maintenance model (wherein they are only taking corrective steps) to a proactive and predictive model.

It is primarily in the hands of equipment manufacturers to increase reliability by eliminating defects in their systems, but this also goes towards positively affecting maintenance procedures. With fewer defects, the required maintenance procedures are less arduous.

The field of tribology is currently advancing in methods of wear detection and its associated applications of condition monitoring [21]. For mechanical systems, wear rate varies throughout the lifetime of the system; typically wear rate will be high during the run-in period after which a smaller relatively constant level will be reached during standard running. Wear rate continues to increase during wear out to failure of the part/system [22].

Future systems may be able to use real time sensors to inform operators when parts are wearing out. Some examples of these sensors include integrated ultrasonic sensors to monitor bearing health or lubrication film thickness, load cells for excess loading on parts that may cause early wear out or laser alignment sensors for displacement, velocity or acceleration monitoring [21].

Though it may seem attractive, running a machine to unnecessary damage does not, in fact, increase productivity. There may a short term increase in productivity however this increases the wear rate on all parts resulting in a shorter overall lifetime and more expensive procedures to bring the machine back online later. This can include large numbers of spare parts or even complete refurbishment. Capital equipment such as selective soldering platforms always have a limited lifespan, but their productivity throughout can be ensured with proper maintenance.

Conclusions

Selective soldering continues to be a popular connective technology within the microelectronics industry and has reached a stage of maturity where it can be considered to be distinct from wave soldering. The technological challenges faced in the selective soldering process are distinct from wave soldering requiring further innovations in the field. This is exemplified by the adoption of ever smaller diameters of wetted nozzle and the growing need for more efficient pre-heating options for selective soldering manufacturing lines. Often manufacturing lines requiring the use of the small diameter wetted nozzles feature parts which have not had input of an engineer with selective soldering experience.

Selective soldering is often thought of late into the design process and as such the processing parameters required to achieve good soldering are more complicated. With more widespread training, more optimal board designs can allow for more optimal selective soldering (greater speed and better joint quality). Despite this however, selective soldering technology continues to advance enabling the joining of more complex components.

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