SELECTIVE SOLDERING WITH SN3.9AG0.6CU: PROCESS DEVELOPMENT

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ABSTRACT

Selective soldering is a process for soldering thru-hole components on the bottom side of an assembly. In a selective soldering process a robot system is used to pick up the assembly and drag it over a single point select wave, or dip the assembly into multiple nozzles that are mounted on a product specific nozzle plate. In contrast, the soldering process utilizing traditional wave soldering equipment consists of transporting the entire assembly, by means of a conveyor system, over a liquid solder wave.

The implementation of lead-free alloys will affect the thermal load of components and board material due to higher process temperatures. Not all of the components can withstand the high temperatures that they may be exposed to during wave and reflow processes. For this reason selective soldering becomes interesting since in this process only the areas that come into contact with the lead-free solder will reach higher temperatures while other sections and components remain significantly below critical temperature levels.

This paper focuses on the effects of board surface finishes and selective soldering process parameters such as drag speed and solderpot temperatures, on the formation and strength of the solder joints. The analysis shows that the process development and material selection should be optimized per component type. This work was accomplished within the scope of the NEMI Lead Free Assembly and Rework Project.

Keywords: Lead Free, Selective Soldering, NEMI

INTRODUCTION

The need for alternative technologies to solder thru-hole assemblies in a selective, reliable, automated, and timely manner is observed in today's trends of electronic products and lead free requirements. Today's electronic package is one where interconnects and functionality is increasing with a concomitant increase in the mix of surface mount and through hole devices while size and weight decreases. As the ratio of interconnects between surface mount to thru-hole components increases, the importance or utilization of wave soldering diminishes. However, the total elimination of thru-hole components is not feasible for many products. Due to these components, an alternative soldering process, opposed to reflow, is required. For example, Pin in Paste or intrusive reflow is utilized for these purposes but this technology assumes not only that the board is properly designed but also that all components and materials are rated to the temperature regimen of a reflow profile.

The majority of SMT components can be soldered using conventional methods such as reflow or wave soldering. Temperature sensitive thru-hole devices such as connectors, electrolytic capacitors, glass displays, and certain radial components require a separate soldering operation. Many of these components are typically selectively soldered utilizing palettes or at lower temperatures. In the transition to lead free soldering, the process window for soldering these components reduces to the point that an alternative soldering technique is required.

Selective soldering is a technology that allows these components to be individually or multiply soldered to the board without exposing the thru-hole component body to process soldering temperatures, which may be in excess of what the components were originally designed to tolerate without risk of damage. It does this by limiting the heat necessary to solder to a selected temperature and/or area on the board. It also allows for the elimination of gluing, pallets, hand soldering, and ultimately optimizes the quality of the finish product.

Selective soldering utilizes many of the concepts in wave soldering. However, selective soldering varies from wave soldering in aspects such as localized fluxing, minimal preheating, and localized flexible soldering that makes this technique unique onto itself. These differences necessitate a discussion especially in light of lead free processing requirements.

The scope of this work was initiated by a trans-company NEMI workgroup whose focus was on lead free assembly and rework. This subset of experiments was undertaken to provide a preliminary understanding in how the wave and selective soldering process are impacted with the use of lead free alloys. Materials for this project were procured by this NEMI workgroup. This NEMI project consisted of 19 companies and 1 University and started work in 2002.

The overall project was divided into 3 phases. This investigation was performed within the scope of phase 1 and assembly of these boards were complete by the end of Q3 2003.

The goal of this investigation was to identify the impact that various board level, process level, and component level parameters exert on the solder joint formation and joint resulting quality. Specifically, boards containing three different components were assembled on three surface finishes namely Cu-OSP, ENIG, and Imm Ag. The assemblies were visually characterized and cross sectioned. In addition, select boards were subjected to air to air thermal cycling in order to observe the degradation and fatigue of the joint as a function of thermal cycling. The joint strength of the selectively soldered components from processed boards was compared by performing pull testing.

The results of this investigation compliments the efforts that were reported by the NEMI Lead Free Assembly and Rework team at the 2004 IPC–Soldertec Lead Free conference in Amsterdam.[1]

EXPERIMENTAL

Selective soldering process

Process development was performed on a Vitronics Soltec mySelective 6748. The process consists of three basic steps: Fluxing, Preheating, and Soldering. The details of each step is described below.

Fluxing

The board populated with the three through hole components was fluxed using a dropjet fluxer. For a drag soldering process, ~1 mm diameter dropsize of flux was applied to the entire row of pins by controlling the pump frequency and open time on the dropjet fluxer.

Preheating

The board was preheated using IR lamps for 30 seconds at a 60% power. The bottomside board temperature was kept constant for all experiments at ~70°C.

Soldering

The components were soldered utilizing a Selectwave fitted with an 8 mm diameter single point nozzle. The solder was actively flowing over the nozzle in a specific direction that opposes the course of the board as it is soldered. The overflow of the solder is controlled by nozzle design. The 8 mm nozzle is surrounded by a 50 liters per minute, lpm, flow of nitrogen gas. The board was held at an angle of 10° by means of a robotic gripper.

In this investigation, the goal was to determine the optimized process for each component. The experimental design includes varying solderpot temperature, drag speed, and surface finish in order to identify the impact each one exerts on the solder joint quality. The specific variation for each parameter is specified in Table 1. Determination for the materials used and the levels for solderpot temperature and drag speed were dictated by availability of the test vehicle and components. The agreed upon temperatures and drag speeds is indicative of typical selective soldering processes used in production.

Table 1. Experimental Parameters Studied

Surface Finish	Solderpot Temperature (°C)	Drag Speed (mm/sec)
ENIG	280	2
		5
	300	2
		3.5
		5
		8
OSP	280	2
		5
	300	2
		3.5
		5
		8
	320	5
		8
		10
Silver	300	3.5

Materials

Flux: For all selective experiments a VOC-free, rosin/resin free no clean flux was utilized.

Components: In total 3 components were soldered. Select properties of the three components are listed in Table 2.

Board: The 4 layer board was constructed with Turbo Clad 370 laminate material to a thickness of 93 mil.

Three board finishes were studied including Cu-OSP (standard Entek 106AX), immersion silver, and ENIG.
Alloy: Only one alloy, high purity Sn3.9Ag0.6Cu was studied due to availability of samples.

Table 2. Component List

Component	Finish	Lead Count
Plastic Frame connector	SnPb	96
Metal Frame connector	SnPb	50
Shunt	Gold	8

Cross sectioning
Several samples were prepared from each category listed in Table 1 for cross section analysis. The method used for cross sectioning consisted of cutting the component in question and potting it in a two-part curing epoxy mixture[2]. After curing overnight, the samples were polished following the basic procedure for grinding and polishing[3]. The goal of cross sectioning specific components was to observe the formation of the lead free solder joints. In order to characterize this, grinding and polishing of the cross section proceeded until it reached the plane where the solder is located between the via and the pin. At this point, it is possible to observe and characterize thru-hole penetration, solder surface, and potential component body damage.

Pull test
This test was performed on the plastic 96 pin connector using an Instron instrument model 550R which was equipped with a special test fixture shown in Figure 1. This test fixture is designed to pull pins perpendicular to the board. The crosshead speed for the pull test was set at 2.54 mm/min for all samples and the load cell had a maximum capacity of 5kN.

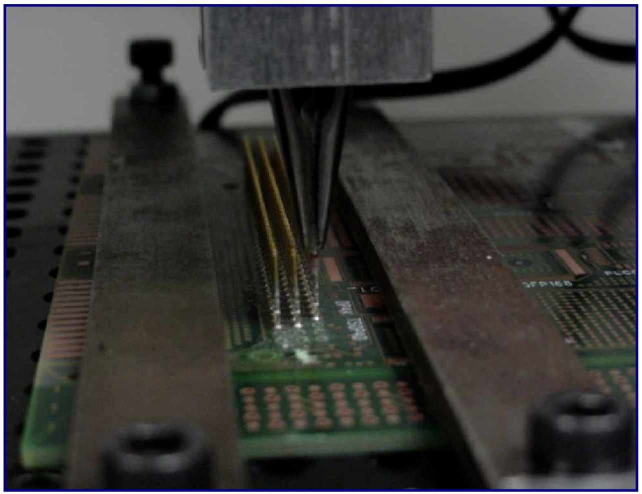


Figure 1. Test Fixture for Pull Test

Thermal cycling
Boards were exposed to -40°C to +125°C air – air thermal cycling. Dwell time at the extremes was 10 minutes with a ramp rate of 10°C/min between the extremes. Samples were placed vertically parallel to air flow. Samples were pulled out at 750, 1200, 2000, and 2700 cycles.

Results

Inspection criteria

The soldered boards were visually inspected after the selective soldering process for the presence of the following defects:

- Poor Pad Wetting was defined as less than 100% solder coverage of the annular ring or the degree of the ring trace exposure.
- Poor Topside Fillet was defined as the amount of solder that wetted the component lead and includes poor thru-hole fill which is less than 100% barrel fill.
- Solder excess
- Solder oxides
- Bridging
- Solderballing
- Skips or Opens

These criteria were developed to remove any ambiguities in characterizing the quality of the solder joint. This inspection technique identifies a conservative method for acceptability and does not coincide with IPC standard 610C for Topside Fillet and Pad Wetting. The philosophy behind the decision to adopt these inspection criteria was to be as critical as possible for ranking the different processes.

The method to evaluate or rank the soldering processes was to first count and sum the defects observed per characteristic. This was followed by assigning a weighted percentage to each inspection criteria category. After calculating the weighted defect level for each characteristic, the sum for all defects was calculated. In order to observe significant changes in the results, the inverse of the total defect sum is reported.

This calculation method was applied to the individual components rather than to the board. In this manner, the individual components were ranked rather the board since selective soldering provides the flexibility to optimize the process per component. The components are ranked and listed in order of best possible joint quality with a higher number representing a better result. Poor pad wetting, poor topside pad wetting, and bridging were the major defects observed and weighted more than the solder excess, solderballing, skips, and oxides. The rankings for the three components are listed in Table 3, 4, 5.

Table 3. Inspection Ranking of 96 Pin Plastic Connector.

96 Pin Plastic Connector			
Drag Speed (mm/sec)	Temp (°C)	Surface Finish	Weighted Average
2	300	ENIG	16.67
2	280	OSP	11.43
3.5	300	OSP	11.25
2	280	ENIG	10.00
2	300	OSP	10.00
3.5	300	ENIG	9.29
5	320	OSP	8.67
5	300	OSP	7.50
3.5	300	Imm Ag	6.25
5	280	ENIG	5.00
5	300	ENIG	5.00
8	320	OSP	4.55
10	320	OSP	4.55
8	300	ENIG	3.13
8	300	OSP	2.50
5	280	OSP	1.92

Table 4. Inspection Ranking of 8 Pin Gold Connector.

8 Pin Gold Connector			
Drag Speed (mm/sec)	Temp (°C)	Surface Finish	Weighted Average
5	280	OSP	100.0
5	320	OSP	65.0
10	320	OSP	50.0
3.5	300	OSP	45.0
8	300	OSP	25.0
8	320	OSP	25.0
5	300	OSP	21.4
3.5	300	Imm Ag	20.0
3.5	300	ENIG	6.2
2	280	OSP	5.2
2	280	ENIG	4.8
5	300	ENIG	4.4
2	300	ENIG	4.2
2	300	OSP	4.2
8	300	ENIG	3.6
5	280	ENIG	2.8

Table 5. Visual Inspection Ranking of 50 Pin Metal Connector

50 Pin Metal Connector			
Drag Speed (mm/sec)	Temp (°C)	Surface Finish	Weighted Average
2	300	ENIG	50.00
3.5	300	Imm Ag	8.33
2	280	ENIG	3.49
3.5	300	ENIG	3.05
3.5	300	OSP	2.65
5	320	OSP	2.60
2	300	OSP	2.27
2	280	OSP	2.26
5	300	OSP	2.24
5	280	OSP	1.92
5	300	ENIG	1.85
8	320	OSP	1.79
10	320	OSP	1.61
5	280	ENIG	1.56
8	300	ENIG	1.52
8	300	OSP	1.32

Pull test results

The pull test results were obtained by characterizing the maximum load at peak and is reported in kN. Table 6 lists the pull strength force for those samples processed under different soldering process for the 96 Pin Plastic Connector. Table 7 lists the pull strength force for those samples that were thermal cycled with baseline to time zero.

Table 6. Pull Force Strength for the 96 Pin Plastic Connector Under Different Process Parameters

Board Finish	Drag Speed	Solder Temperature	Pull Force (kN)	Standard Deviation
CuOSP	3.5 mm/sec	300 C	0.29	0.02
ENIG	3.5 mm/sec	300 C	0.33	0.02
Imm Ag	3.5 mm/sec	300 C	0.30	0.03
CuOSP	5 mm/sec	280 C	0.29	0.02
CuOSP	5 mm/sec	320 C	0.30	0.03
CuOSP	8 mm/sec	300 C	0.29	0.02
CuOSP	2 mm/sec	300 C	0.31	0.03
CuOSP	5 mm/sec	300 C	0.31	0.03

Table 7. Pull Force Strength for the 96 Pin Plastic Connector Exposed to Thermal Cycling

Board Finish	Drag Speed	Solder Temperature	Thermal Cycles	Pull Force (kN)	Standard Deviation
CuOSP	3.5 mm/sec	300 C	0	0.29	0.02
CuOSP	3.5 mm/sec	300 C	750	0.26	0.02
CuOSP	3.5 mm/sec	300 C	1200	0.28	0.02
CuOSP	3.5 mm/sec	300 C	2000	0.28	0.01
CuOSP	3.5 mm/sec	300 C	2700	0.29	0.04

The results observed in the pull test are influenced by the failure mode of the system studied. There are at least three possible failure modes in this pull test experiment. They include lead fracture, barrel cracking and failure, and lastly, solder cracking and failure.

DISCUSSION

Effect of board surface finish

In this study three board finishes were studied including CuOSP, ENIG, and Imm Ag. A trend was observed between the board surface finish but also component type. This illustrates the multitude of opportunities that exist when employing selective soldering. Table 8 lists the results based on board surface finish as well as component type. All other variables were kept constant: solder temperature at 300°C and drag speed at 3.5 mm/sec.

Table 8. Ranking of Defects as a Function of Board Surface Finish and Component Type.

Board Finish	Weighted Average	TH Component
OSP	45.0	8 Pin Gold
Imm Ag	20.0	8 Pin Gold
ENIG	6.2	8 Pin Gold
OSP	11.25	96 Pin Plastic Conn
ENIG	9.29	96 Pin Plastic Conn
Imm Ag	6.25	96 Pin Plastic Conn
Imm Ag	8.33	50 Pin Metal Conn
ENIG	3.05	50 Pin Metal Conn
OSP	2.65	50 Pin Metal Conn

The results listed in Table 8 exemplify that the trend with board finish is dependent on the specific component. For example, the use of CuOSP worked best for the 8 Pin Gold Shunt and the 96 Pin Plastic Connector. However, the combination of the 50 Pin Metal Connector with CuOSP board finish resulted in the worst overall soldered joint and/or component.

Interpreting the weighted average in terms of quality and ultimately solder process optimization is subjective depending upon the criteria used to inspect a solder joint. In this investigation a minimum weighted average of 6.00 or greater indicates a process that yields minimal defect levels and consequently minimal need for rework. Below this level it is possible to make significant improvements in the soldering process. Taking this metric for acceptability, CuOSP performed very well for the 8 Pin Gold Connector and 96 Pin Plastic Connector while performing poorly with the 50 Pin Metal Frame Connector. While Imm Ag yielded very good soldering results on the 50 Pin Metal Frame Connector, it did not duplicate this result for the other two connectors. However, it must be stated that only 1 condition was tested with Immersion silver as the board finish. So it remains possible that the soldering process may be optimized for all three components with Immersion Silver board finish. Images of cross sections of the 50 Pin Metal Frame Connector are shown in Figures 2, 3, 4 for each board finish. Here it can be observed that voiding was more prominent when using Imm Ag.

Figure 2. Thru-hole Penetration for the 50 Pin Metal Frame Connector on Imm Ag.

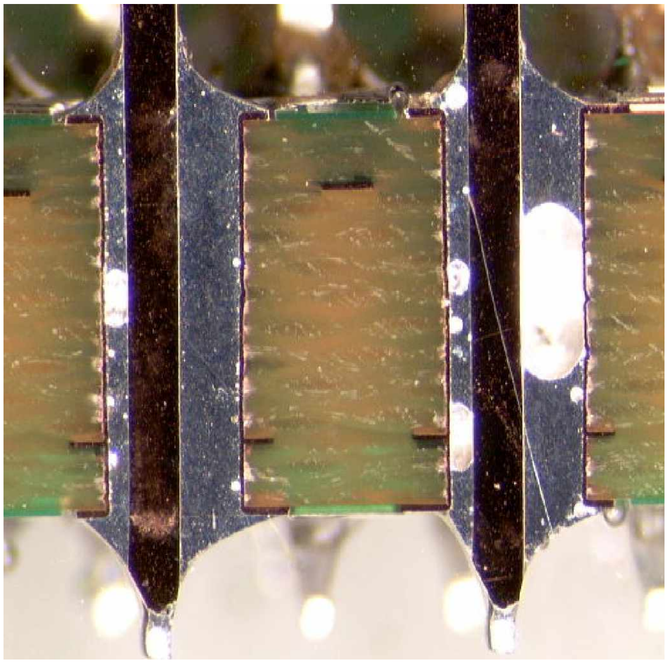


Figure 3. Thru-hole Penetration for the 50 Pin Metal Frame Connector on ENIG.

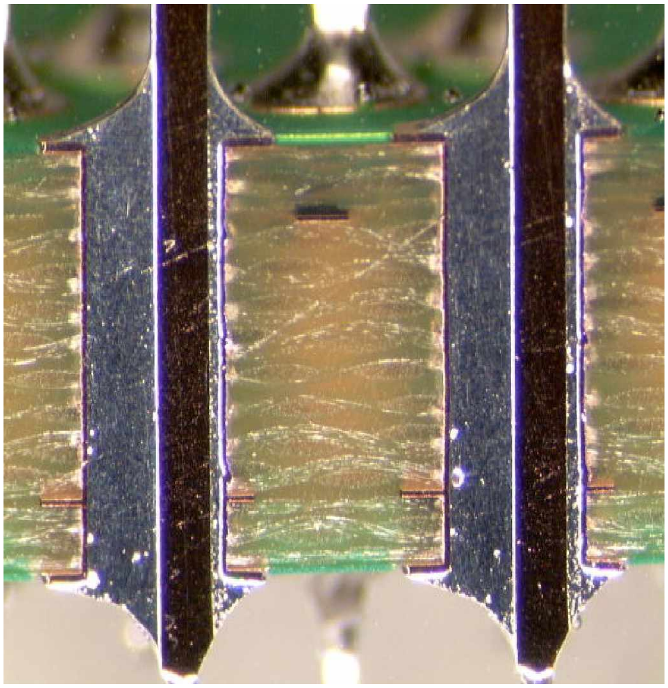


Figure 4. Thru-hole Penetration for the 50 Pin Metal Frame Connector on CuOSP.

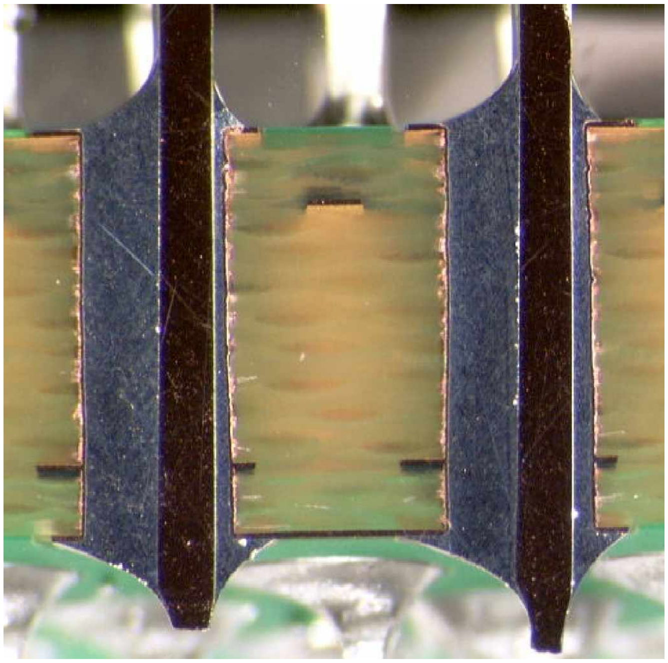


Table 9 shows the results of the pull test per board finish. The results from the pull test showed that for the CuOSP samples, 100% of the failure were due to barrel cracking and failure. However, the ENIG and Imm Ag board finished samples failed due to both solder and barrel failure. As a result of this observation, the only conclusion that can be reached is that the solder joint is stronger than the barrel and board. This is confirmed by the consistent pull forces at peak load for all of the samples. The ENIG and Imm Ag boards are slightly different but still closely match the results from the CuOSP boards.

Table 9. Pull Force Strength for the 96 Pin Plastic Connector

Board Finish	Drag Speed (mm/sec)	Solderpot Temperature (C)	Pull Force (kN)	Standard Deviation
CuOSP	3.5	300	0.29	0.02
ENIG	3.5	300	0.33	0.02
Imm Ag	3.5	300	0.3	0.03

Effect of solderpot temperature

In this study, three solder temperatures were studied to identify the impact it will exert on soldering a thru-hole joint. The three solder temperatures were used: 280°C, 300°C, and 320°C. In this comparison, all other variables were kept constant at the following levels: drag speed at 5.0 mm/sec with a board finish of CuOSP. The results as listed in Table 10 below illustrate trends based on both solder temperature and component type. Based on this a selection of temperature should be made based on the most difficult component which was consistently the 50 Pin Metal Frame Connector.

Table 10. Impact of Solder Temperature on Soldering Joint Quality

Temp (C)	Weighted Average	Component
320	8.67	96 Pin Plastic Conn
300	7.50	96 Pin Plastic Conn
280	1.92	96 Pin Plastic Conn
280	100.00	8 Pin Gold Conn
320	65.00	8 Pin Gold Conn
300	21.43	8 Pin Gold Conn
320	2.60	50 Pin Metal Conn
300	2.24	50 Pin Metal Conn
280	1.92	50 Pin Metal Conn

The solder temperature impact on solder joint quality for the 8 Pin Gold Shunt is acceptable at all three temperatures while the 96 Pin Plastic Connector has acceptable joint quality at 320°C and 300°C. The 50 Pin Metal Frame Connector results in marginal process solution over the three temperatures at 5 mm/sec. In this case, the solder temperature of 280°C yields a process that is unacceptable for 2 out of the 3 components.

Figures 5, 6, 7 illustrate the behavior of hole fill at the three solder temperatures. At 5 mm/sec drag speed and on CuOSP, the solder fills the barrel completely in all three cases but topside pad wetting varies as a function of solder temperature.

Figure 5. Solder Joint Formed at 280°C on the 50 Pin Metal Frame Connector

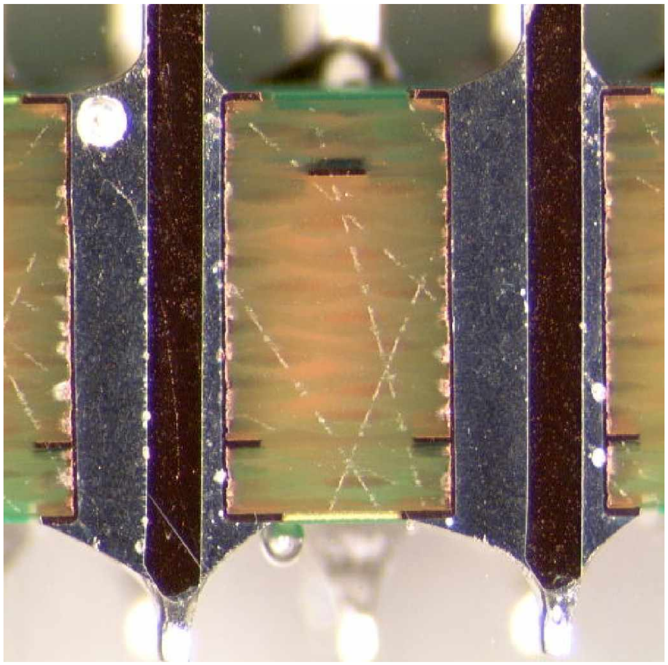


Figure 6. Solder Joint Formed at 300°C on the 50 Pin Metal Frame Connector

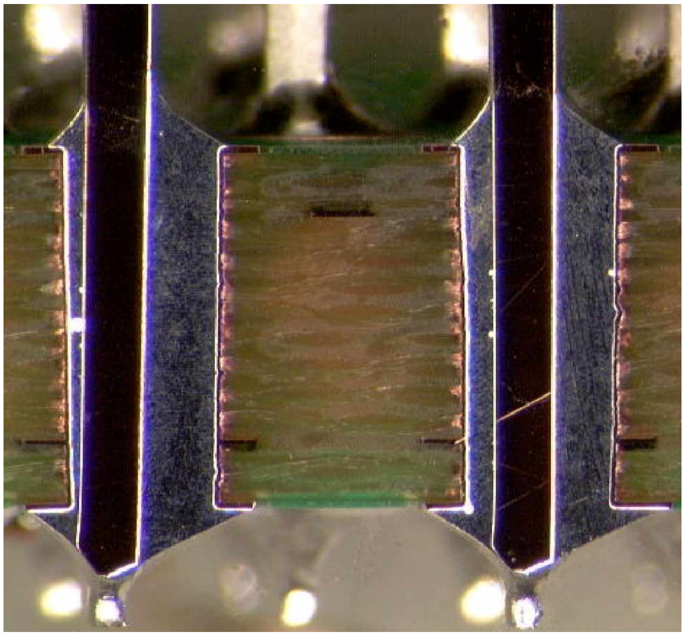
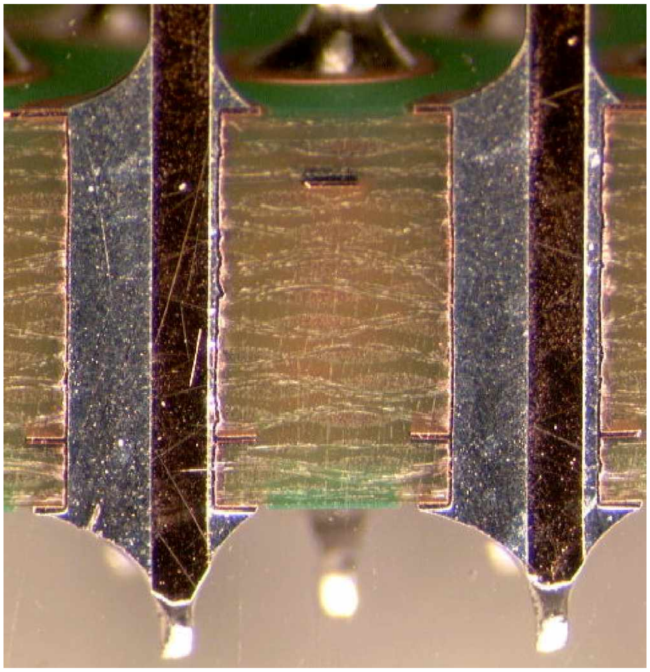


Figure 7. Solder Joint Formed at 320°C on the 50 Pin Metal Frame Connector



In this case, solder joints formed at 320°C showed an improvement of the topside wetting when compared to the other two scenarios.

Pull test results as a function of pot temperature are listed in Table 11. In this case, the drag speed and the surface finish were kept constant at 5 mm/sec and CuOSP respectively.

Table 11. Pull Force Strength for the 96 Pin Plastic Connector.

Board Finish	Drag Speed (mm/sec)	Solderpot Temperature (°C)	Pull Force (kN)	Standard Deviation
CuOSP	5	280	0.29	0.02
CuOSP	5	300	0.31	0.03
CuOSP	5	320	0.30	0.03

As indicated by the pull force and respective standard deviation, the results are statistically equal in all three cases. Moreover, failure mode that was observed in all cases was barrel failure and cracking. This indicates that the solder joint was stronger regardless of solderpot temperature as well as topside pad wetting. This leads to the conclusion that topside pad wetting is not critical for joint performance. Consequently, selection of pot temperature is not critical for the 96 Pin Plastic Connector.

Effect of drag speed

In this study, the impact of four drag speeds was studied including, 2, 3.5, 5, 8 mm/sec. All other variables were kept constant: CuOSP board finish and 300°C solder temperature. Drag speed directly affects the contact time. The trend observed over all three components is a consistent optimized drag speed equal to 3.5 mm/sec. At this drag speed, the best solder joint quality was achieved compared to the other drag speeds as listed in Table 12.

Table 12. Impact of Drag Speed on Solder Joint Quality.

Drag Speed (mm/sec)	Weighted Average	Component
3.5	11.25	96 Pin Plastic Conn
2	10.00	96 Pin Plastic Conn
5	7.50	96 Pin Plastic Conn
8	2.50	96 Pin Plastic Conn
3.5	45.00	8 Pin Gold Conn
8	25.00	8 Pin Gold Conn
5	21.43	8 Pin Gold Conn
2	4.17	8 Pin Gold Conn
3.5	2.65	50 Pin Metal Conn
2	2.27	50 Pin Metal Conn
5	2.24	50 Pin Metal Conn
8	1.32	50 Pin Metal Conn

However, a difference is observed in terms of defect level. The 50 Pin Metal Frame Connector yields a defect level that is consistently and significantly high compared to the other two components. As a result other variables will be necessary for proper optimization.

The results of the pull test are shown in Table 13. As in the results observed for the impact of solderpot temperature, the drag speed has no observable impact on the pull force and failure mode of the 96 Pin Plastic Connector joints.

Table 13. Impact of Drag Speed on Pull Force of the 96 Pin Plastic Connector.

Board Finish	Drag Speed (mm/sec)	Solderpot Temperature (°C)	Pull Force (kN)	Standard Deviation
CuOSP	2	300	0.31	0.03
CuOSP	3.5	300	0.29	0.02
CuOSP	5	300	0.31	0.03
CuOSP	8	300	0.29	0.02

Effect of aging

In this study, select boards were thermal cycled under the conditions defined in the experimental. Analysis primarily focussed on performing pull tests as well as examining the cross sections. As previously discussed, the results from the pull test of the 96 Pin Plastic Connector did not yield conclusive information on the selective soldered boards since the failure mode was barrel cracking. Figures 8 - 12 illustrate the surface and microstructure evolution of the solder joint.

Figure 8. Solder Joint at Time Zero (Entire Joint and Close-up)

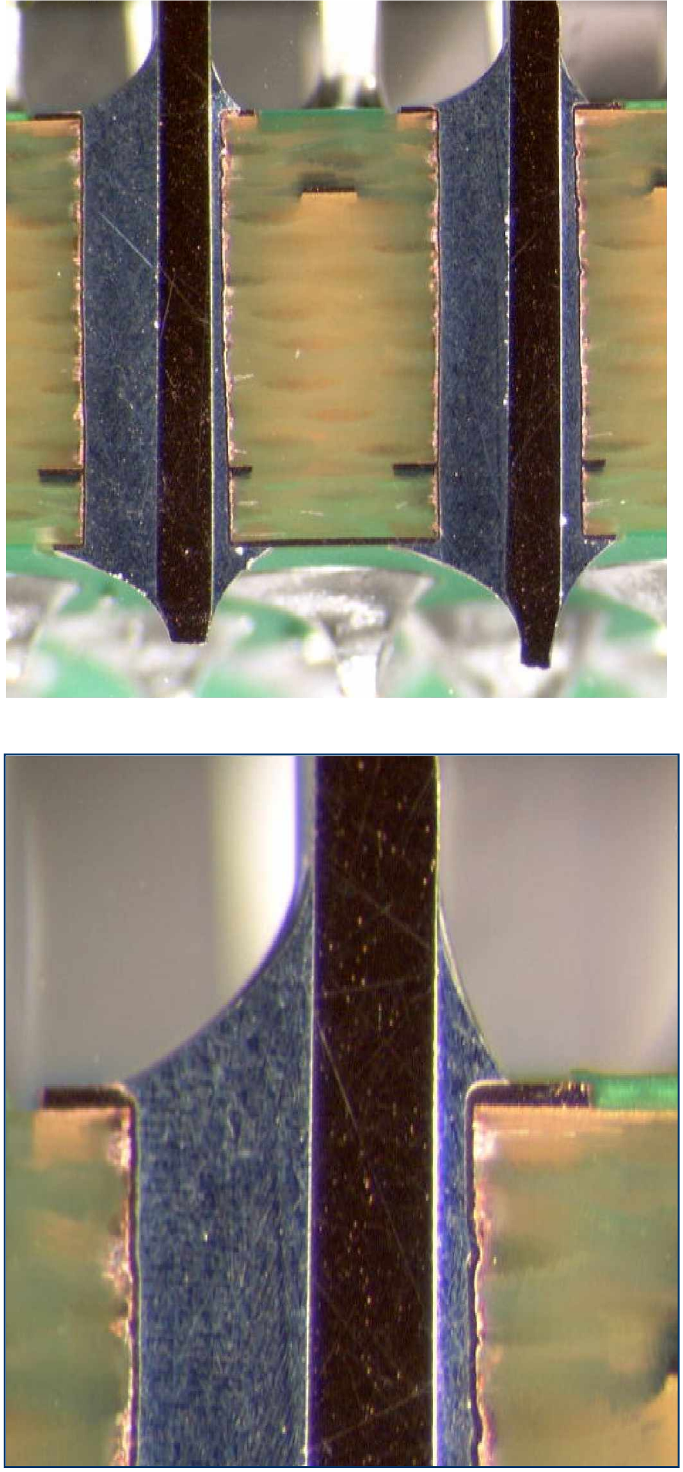


Figure 9. Solder Joint after 750 Cycles (Entire Joint and Close-up)

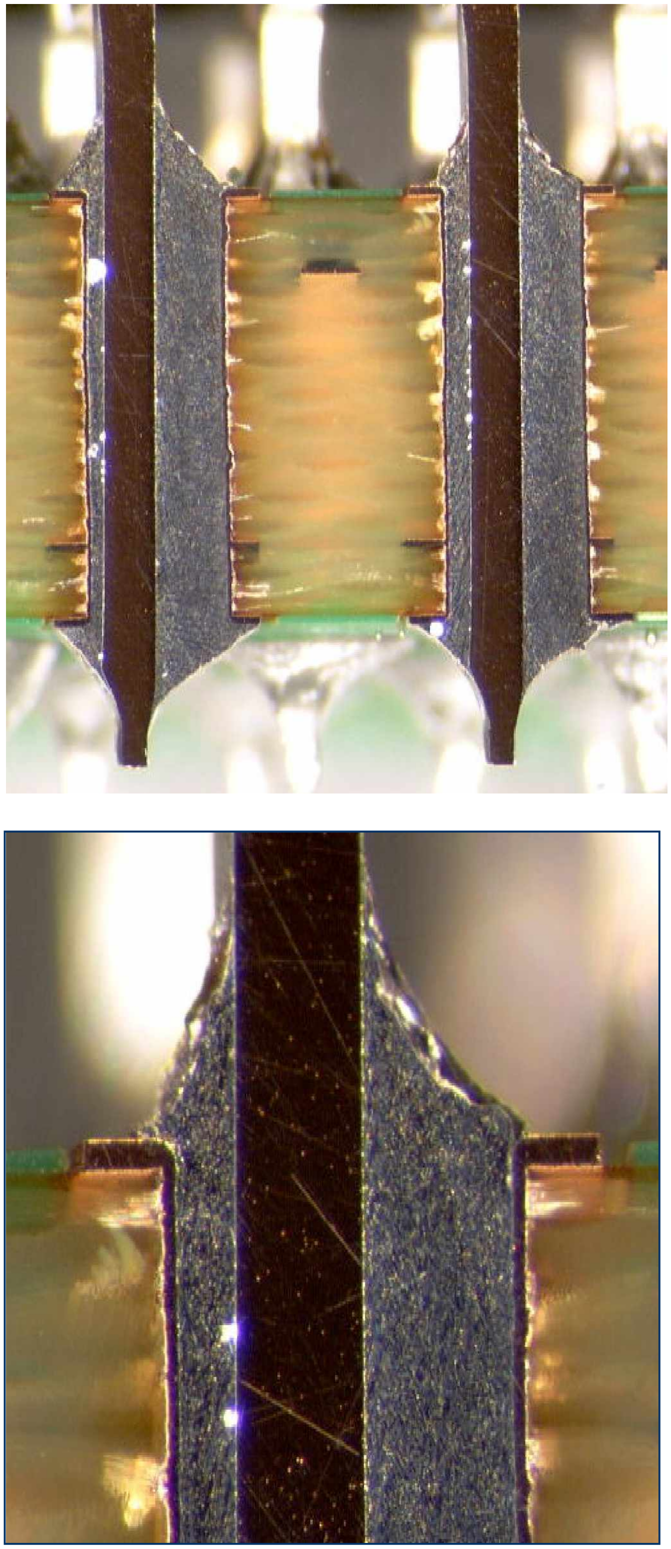


Figure 10. Solder Joint after 1200 Cycles (Entire Joint and Close-up)

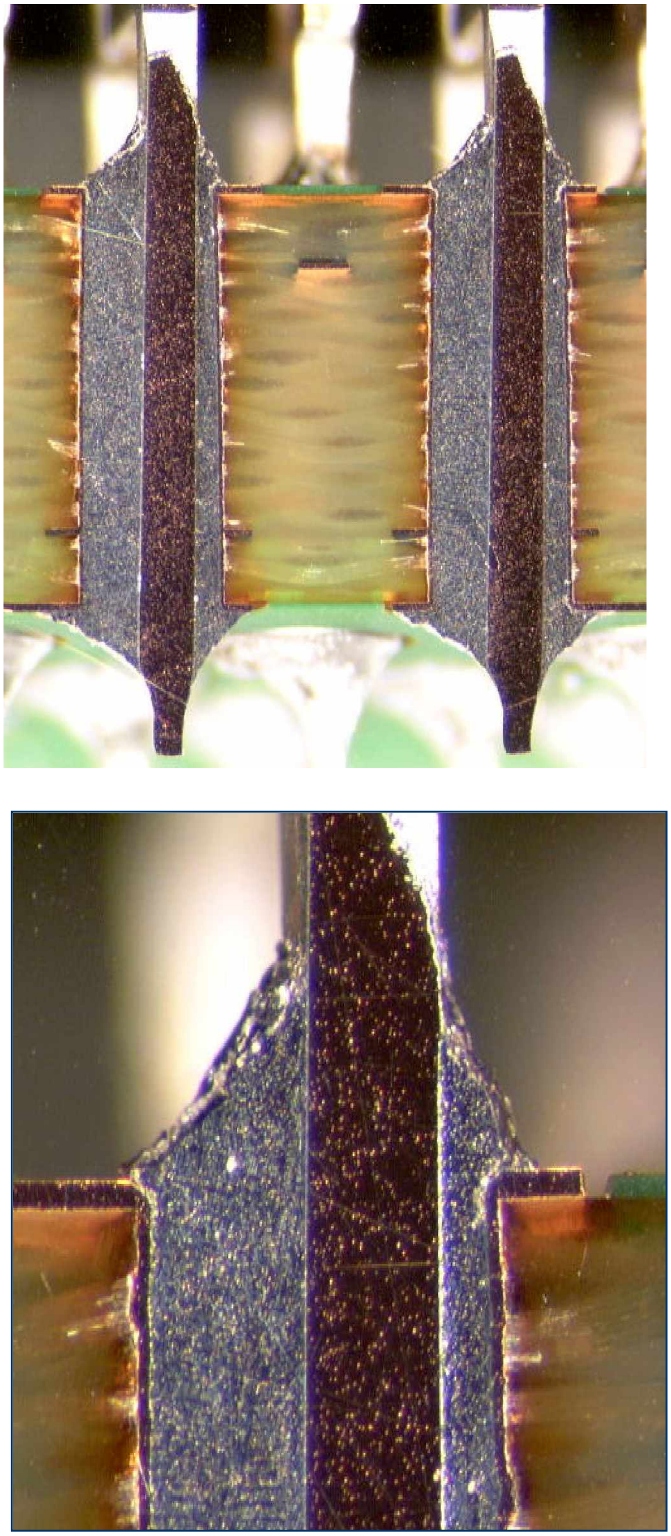


Figure 11. Solder Joint after 2000 Cycles (Entire Joint and Close-up)

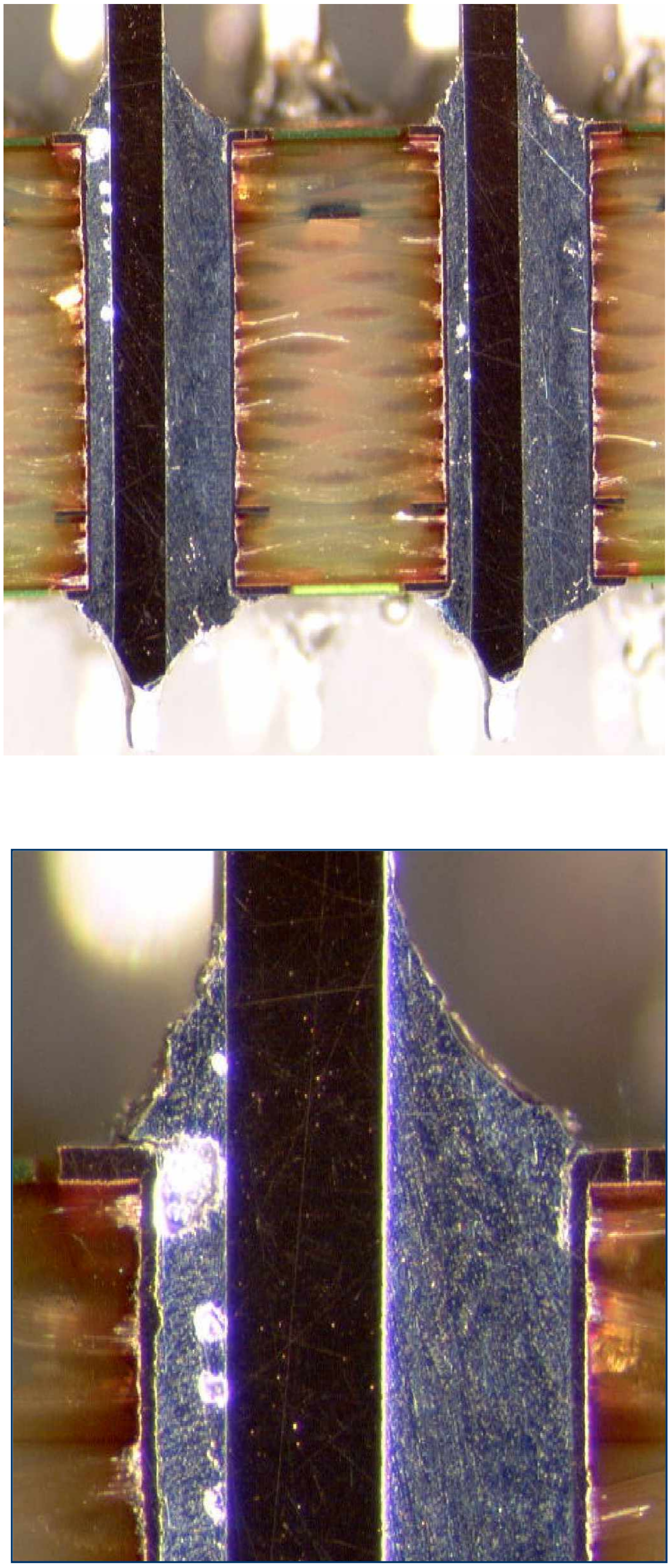
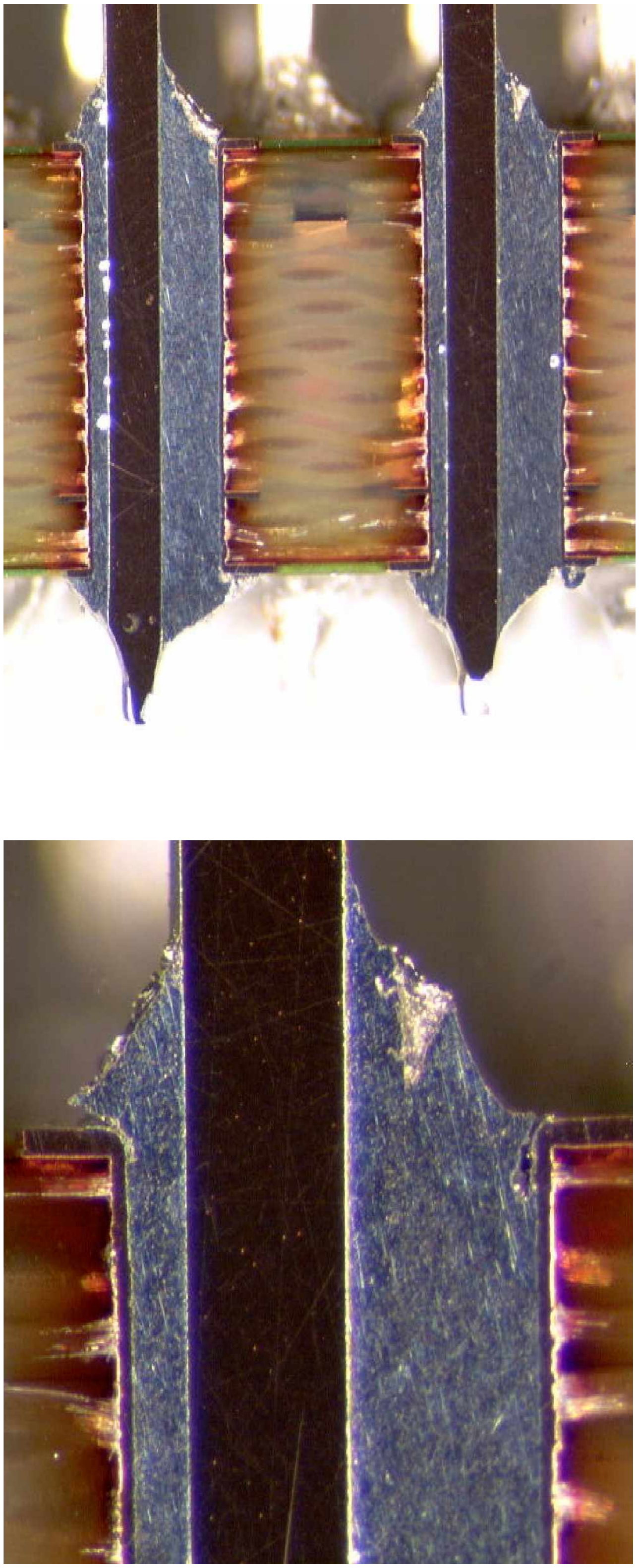


Figure 12. Solder Joint after 2700 Cycles(Entire Joint and Close-up)



The images show a degradation of the joint over thermal cycling. Voiding, shrink holes, and cracks are observed to increase in size and frequency as a function of cycling. However, there no signs of complete fracture of the joint, which can jeopardize the interconnection.

Interestingly, a comparison of the 96 Pin Plastic Connector pull test results listed in Table 7 obtained on samples that were selectively soldered to the 96 Pin Plastic Connector pull force results of those boards soldered by traditional wave soldering is quite different. Complete analysis of this system soldered by traditional wave soldering is in progress at this time[4]. However, Table 14 lists the pull force of the 96 Plastic Pin Connector for a CuOSP finished board at a solderpot temperature of 260°C, dwell time of 6 seconds, topside preheat temperature of 110°C fluxed utilizing an Organic Acid Cleaning Flux. The failure mode observed in this experiment was also found to be solely barrel failure but yet the Pull Force decreases significantly as a function of thermal cycling.

Table 14. Pull Force of the Thermal Cycled 96 Pin Plastic Connector Soldered Utilizing Traditional Wave Soldering.

Board Finish	Solder Temperature	Thermal Cycles	Pull Force (kN)	Standard Deviation
CuOSP	260 C	0	0.29	0.02
CuOSP	260 C	750	0.23	0.03
CuOSP	260 C	1200	0.21	0.04
CuOSP	260 C	2000	0.21	0.02
CuOSP	260 C	2700	0.20	0.02

The critical difference between the results shows that the joints formed by selective soldering were stronger versus those joints formed by traditional wave soldering.

CONCLUSION

The purpose of this study was to identify the impact various parameters exert on the solder joint formation and defect level. Trends were observed based on drag speed, board surface finish, solder temperature. Also important was the type of component. On this board three through hole components were included. Each component is characterized by unique finish, thermal properties, pin count, etc… A combination of board level, component level, and process level parameters resulted in a soldering process that is optimized at different parameter levels. The flexibility in automating a soldering process that is adjustable for drag speed, solder angle, dip soldering, and possibly solder temperature can result in optimization of solder joint quality.

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