ICT Probe Penetrability of Solder Paste Flux Residues with a Vacuum-Actuated Fixture

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Abstract
All but the most simple circuit boards processed in recent times are inspected using in-circuit testing, ICT. In order to test on pads or connections printed with no-clean solder paste; the post-reflow flux residue must be easily penetrated by ICT pin-probes. Additionally, the electronics industry continues to move from tin-lead solder alloys to various lead-free alloys, particularly the tin-silver-copper alloys that usually require hotter reflow profiles. The hotter reflow conditions required for lead-free solder paste influence the consistency of the solder paste flux's residue and its suitability for in-circuit testing, often producing a hard, brittle residue that is difficult to pin probe.

A new method of evaluating solder paste flux residue penetrability has been developed. Because most circuit assembly plants use vacuum actuated fixtures, this method uses a common, multi-probe ICT fixture, modified and wired so the probe-to-pad resistance can be evaluated using a very sensitive 4-wire resistance measurement. This method allows measurement of resistances as low as 30 mΩ. Four probe forces, three tip shapes and two probe densities have been incorporated into the fixture, so the optimum probe shape and minimum force required to successfully penetrate the solder paste's residue can be determined. Results are presented for the ICT probe penetrability of the flux residue of several different solder pastes after being processed with different reflow conditions.

Introduction
Soldering materials suppliers want to provide materials with easily probed flux residues because all but the simplest circuit boards processed in recent times are inspected using ICT. In order to test on pads or connections printed with no-clean solder paste; the post-reflow flux residue must be easily penetrated by ICT pin-probes. Additionally, the electronics industry continues to move from tin-lead solder alloys to various lead-free alloys, particularly the tin-silver-copper alloys that usually require hotter reflow profiles. The hotter reflow conditions required for lead-free solder paste influence the consistency of the solder paste flux's residue and its suitability for in-circuit testing, often producing a hard, brittle residue that is difficult to pin probe.

In the past, a method was developed to evaluate ICT probe penetrability of no-clean, solder paste flux residues using modified Camalot dispensing system as a high-speed, accurate x-y table with a z-axis head for "flying probe" pin testing [1,2]. This method provided contact resistance measurements for several thousand mechanical probe-to-pad contacts with a single ICT probe. However, this method did not always predict which materials circuit assemblers would find easy or difficult to pin-test. While this method provides useful information on flux residue build-up on ICT probes and its influence on continued residue probe-ability after many mechanical contacts, it only provides information on one type of probe. Most circuit assemblers use vacuum-actuated "bed of nails" or "clamshell" fixtures with multiple ICT probes with different probe shapes, forces and probe densities, all of which influence the ease of the probe to make a good electrical contact. A flux residue penetrability evaluation method that is closer to actual industrial ICT testing may provide more predictive information. Therefore, a test method was developed using a vacuum-actuated fixture.

One problem encountered was determining the maximum contact resistance that circuit assemblers would consider acceptable electrical continuity. In the previous method, any resistance under 5 Ω was considered a good contact; in practice this would be the sum of two probes to pad contact resistances, plus the resistance of any circuitry in the fixture and ICT tester. The contribution of the fixture and ICT measurement device can be as high as three ohms, so for a maximum contact resistance of 5 Ω, the combined resistance of the two probe contacts should be less than 2 Ω, or 0.5 to 1 Ω each. A four pole resistance measurement should be used to determine resistances below 1 Ω

Methodology Description
A commercially available, vacuum-actuated ICT fixture from Everett Charles Technologies was obtained, see **Figure 1.**, and wired to allow 4 pole resistance measurements using a commercially available multiplexer with a built-in multi-meter. ICT test devices are expensive because they can be programmed to make variety measurements, not need for this test method, and only the most sophisticated units will make 4-pole resistance measurements.

Figure 1. Pin-Testability Fixture

The ICT fixture is equipped with 224 probes, arranged in 14 groups of 16 probes with the same tip shape and 4 different probe forces, as described in Table 1. An illustration of the three tip shapes are given in Figure 2.

Table 1. ICT Probes Used

# Probes	Probe Tip Shape	Probe force	Probe pitch
64	Spear	2 oz	40 mil
8	Spear	2 oz	150 mil
8	Spear	4 oz	150 mil
8	Spear	6 oz	150 mil
8	Spear	8 oz	150 mil
8	Blade	2 oz	150 mil
8	Blade	4 oz	150 mil
8	Blade	6 oz	150 mil
8	Blade	8 oz	150 mil
8	Crown	2 oz	150 mil
8	Crown	4 oz	150 mil
8	Crown	6 oz	150 mil
8	Crown	8 oz	150 mil
8	Crown	2 oz	75 mil
8	Crown	4 oz	75 mil
8	Crown	6 oz	75 mil
8	Crown	8 oz	75 mil
8	Crown	2 oz	100 mil
8	Crown	4 oz	100 mil
8	Crown	6 oz	100 mil
8	Crown	8 oz	100 mil

Figure 2. ICT probe shapes used.

The test vehicle is 62 mils thick FR4, with OSP coated copper laminate and solder mask on both sides. 75 mil and 150 mil pitch crown probes on the fixture are mated with 50 mil round pads without vias, 100 mil pitch crown probes are used with header component in through-holes, and only for evaluating the pin-testability of wave-soldering fluxes. Spear and blade probes are mated with 35 mil pads with 12 mil vias.

Flux residue collects in the via during solder paste reflow; this tiny pool of flux residue is difficult to probe. The vehicle allows double-sided testing with solder pastes, one side with single reflowed paste and the opposite side with double reflowed paste. The test vehicle is placed in the ICT test fixture, and vacuum is connected to the fixture, causing the ICT pins to be pulled up onto the vehicle.

The multiplexer makes a 4-pole contact resistance measurement for each of the 224 ICT probes in the fixture to their corresponding soldered test pad. The probes themselves have a resistance that ranges from 30 – 80 mΩ and the added resistance of the coupon is less than 10 mΩ so this method is capable of measuring probe-pad contact resistances less than 500 mΩ. National Instruments LabView software was used to write the Virtual Instrument program that collects the resistance data from the multiplexer and saves the data from many sets of measurements to an ASCII file that can be processed using Microsoft Excel.

Experimental Procedure

In this paper, a study of the ICT probe penetrability of three lead-free, no-clean solder pastes pin reflowed with three different temperature vs. time profiles will be presented. Pastes A and B were formulated to be easily penetrated by ICT probes, and Paste C is only moderately pin testable. The reflow conditions include two straight ramps and one soak 160˚C to a peak temperature of 250˚C, see **Figure 3**. Several test vehicles were printed and reflowed on one side, allowed to cool, then printed and reflowed on the other side. After reflow, the test vehicles were allowed to sit at ambient conditions for about 24 hours before ICT testing on both sides. Forty sets of 192 probe contact resistances were made for each paste/reflow condition, twenty each for singly and doubly reflowed solder paste. For solder pastes, the 32 crown probe-to-header contacts are ignored.

Results and Discussion

The ICT probe contact data were analyzed using a combination of Microsoft Excel and Minitab. Statistical resistance values for the different ICT probe used are given in **Table 2**. For Paste a reflowed using profile A. Similar values were calculated for the other eight paste/reflow conditions studied. The 40 mil centered 2 oz spears probes had a minimum resistance of about 0.08 Ω and the other probes had a minimum resistance of about 0.04Ω; these are the resistances of the probes themselves. The crown probes in contact with 50 mil flat pads consistently had low resistance values, about that of the probes themselves, and no dependence on probe spacing was observed. **Figure 4.** Shows a Minitab main effects plot for mean probe resistance against the variables paste, reflow conditions, probe force, probe tip shape and number of reflows.

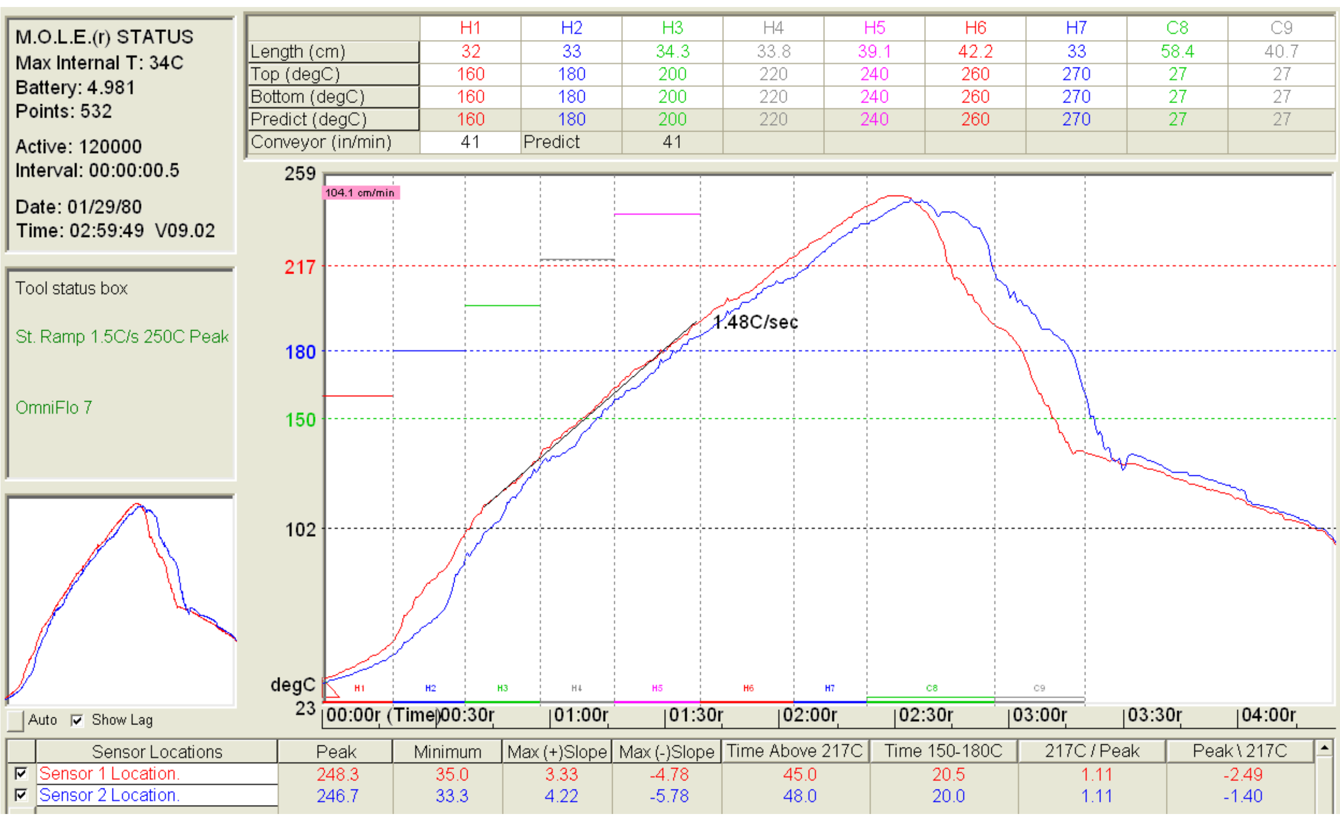

Figure 3.a 1.5C/s straight ramp to 250˚C peak

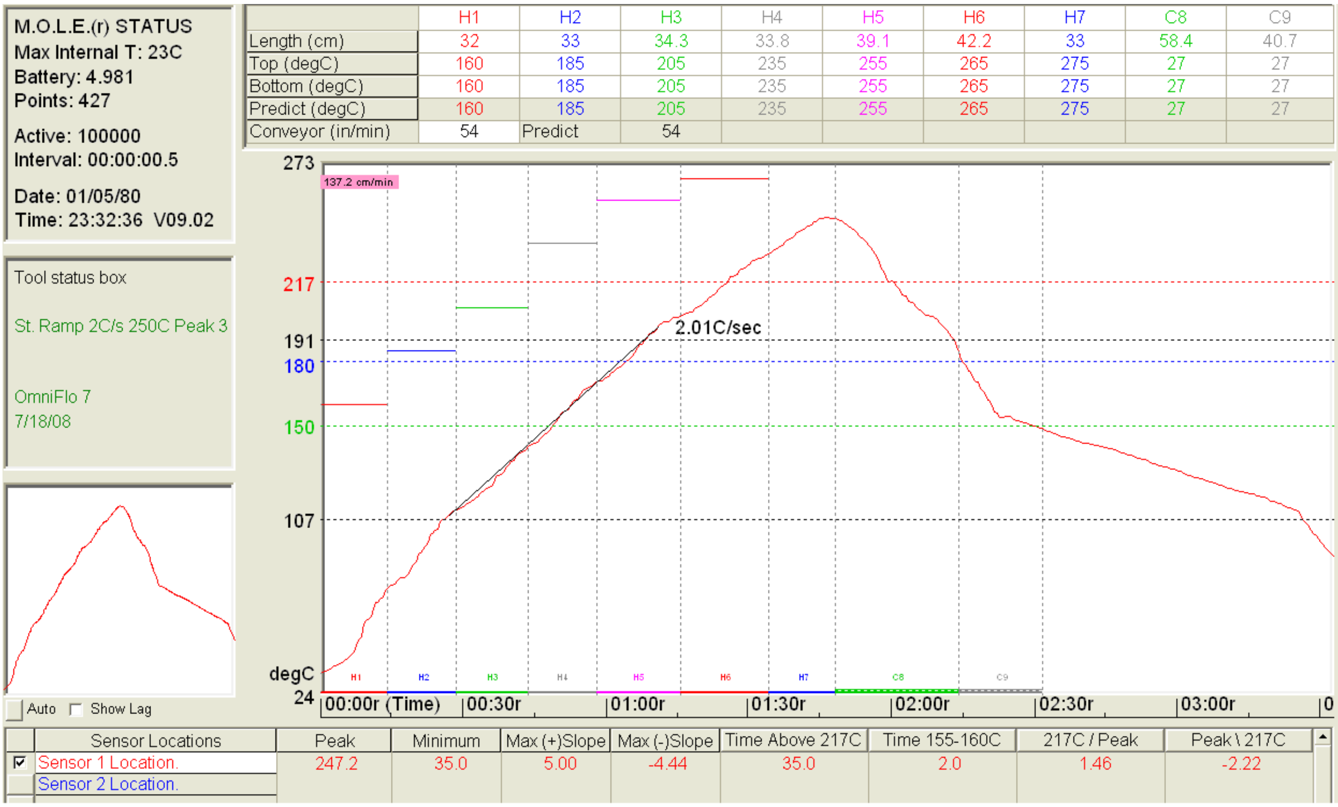

Figure 3.b 2C/s straight ramp to 250˚C peak

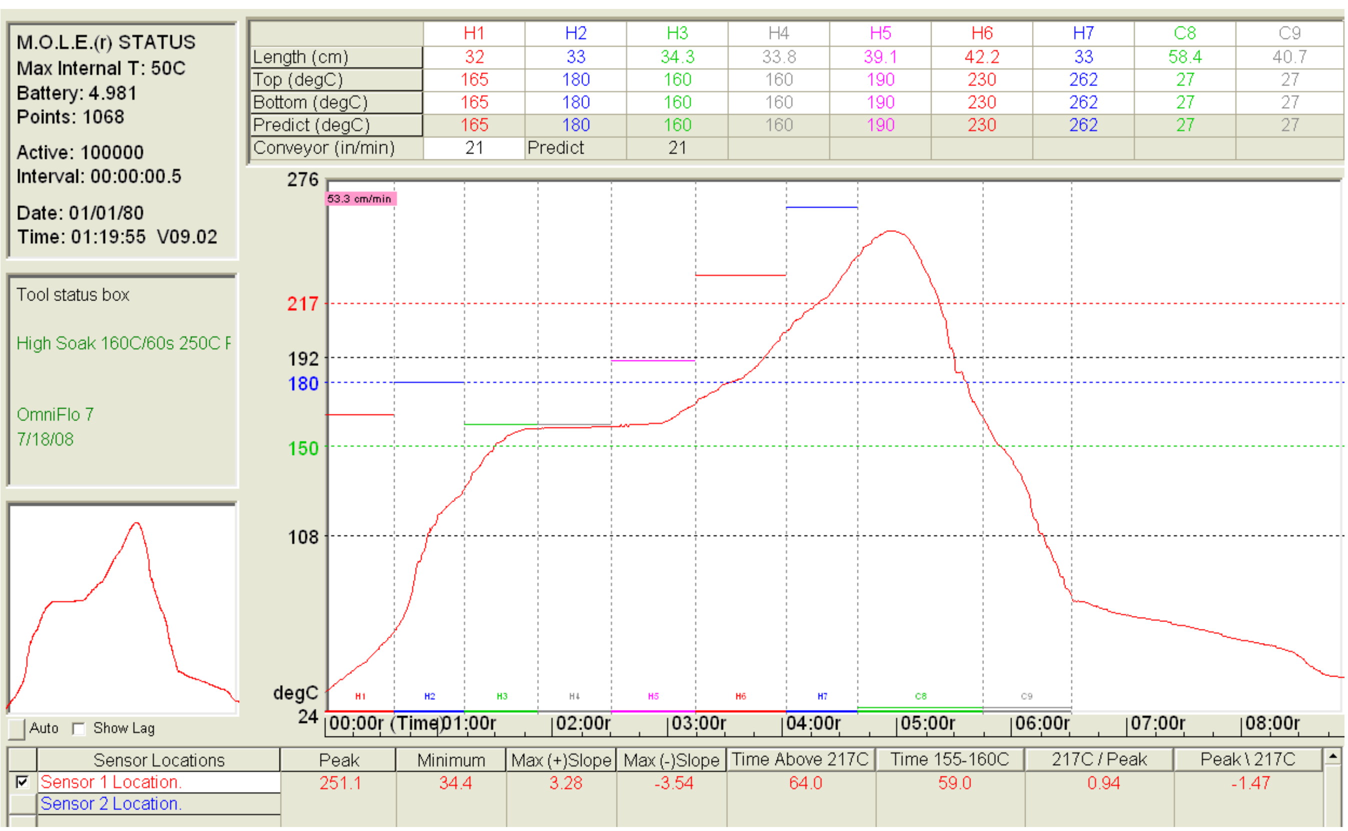

Figure 3.c 60 s soak at 160˚C, 250˚C peak, 60s time above liquidus.

Table 2. Probe resistance value statistics for Paste A reflowed with 160 soak

Probe type	# Reflows	Contacts	Opens >2000 Ω	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
40 mil 2 oz spears	1	1280	0	0.325	0.013	0.478	0.074	0.118	0.181	0.312	5.280
75 mil 2 oz crown	1	160	0	0.042	0.000	0.003	0.038	0.040	0.041	0.044	0.065
75 mil 4 oz crown	1	160	0	0.040	0.000	0.002	0.035	0.038	0.040	0.041	0.046
75 mil 6 oz crown	1	160	0	0.038	0.000	0.001	0.036	0.037	0.038	0.038	0.043
75 mil 8 oz crown	1	160	0	0.037	0.000	0.001	0.036	0.037	0.037	0.038	0.040
150 mil 2 oz blade	1	131	29	0.692	0.079	0.907	0.046	0.071	0.225	1.280	5.640
150 mil 4 oz blade	1	158	2	0.321	0.045	0.570	0.044	0.053	0.072	0.300	3.170
150 mil 6 oz blade	1	160	0	0.385	0.041	0.523	0.039	0.050	0.136	0.394	2.250
150 mil 8 oz blade	1	160	0	0.131	0.016	0.206	0.040	0.047	0.051	0.148	1.780
150 mil 2 oz crown	1	160	0	0.046	0.000	0.005	0.040	0.042	0.044	0.047	0.076
150 mil 4 oz crown	1	160	0	0.041	0.000	0.003	0.037	0.039	0.040	0.042	0.053
150 mil 6 oz crown	1	160	0	0.039	0.000	0.001	0.037	0.038	0.039	0.040	0.045
150 mil 8 oz crown	1	160	0	0.038	0.000	0.001	0.036	0.037	0.038	0.038	0.039
150 mil 2 oz spear	1	140	20	0.237	0.040	0.478	0.045	0.062	0.107	0.179	3.980
150 mil 4 oz spear	1	160	0	0.062	0.005	0.062	0.043	0.048	0.051	0.057	0.735
150 mil 6 oz spear	1	160	0	0.050	0.001	0.016	0.041	0.044	0.048	0.052	0.230
150 mil 8 oz spear	1	160	0	0.047	0.000	0.006	0.039	0.042	0.045	0.051	0.066
40 mil 2 oz spears	2	1280	0	0.268	0.014	0.492	0.077	0.125	0.173	0.265	12.000
75 mil 2 oz crown	2	160	0	0.041	0.000	0.002	0.038	0.039	0.041	0.042	0.047
75 mil 4 oz crown	2	160	0	0.039	0.000	0.002	0.035	0.037	0.040	0.041	0.046
75 mil 6 oz crown	2	160	0	0.038	0.000	0.001	0.036	0.037	0.037	0.038	0.042
75 mil 8 oz crown	2	160	0	0.037	0.000	0.001	0.035	0.037	0.037	0.038	0.040
150 mil 2 oz blade	2	160	0	0.572	0.123	1.561	0.045	0.048	0.064	0.696	18.500
150 mil 4 oz blade	2	160	0	0.200	0.025	0.314	0.042	0.046	0.060	0.202	1.960
150 mil 6 oz blade	2	160	0	0.357	0.040	0.501	0.042	0.044	0.117	0.405	2.120
150 mil 8 oz blade	2	160	0	0.102	0.009	0.120	0.040	0.041	0.051	0.113	0.883
150 mil 2 oz crown	2	160	0	0.044	0.000	0.003	0.040	0.042	0.044	0.046	0.056
150 mil 4 oz crown	2	160	0	0.040	0.000	0.003	0.037	0.038	0.040	0.042	0.060
150 mil 6 oz crown	2	160	0	0.039	0.000	0.002	0.037	0.038	0.039	0.040	0.050
150 mil 8 oz crown	2	160	0	0.038	0.000	0.001	0.036	0.037	0.038	0.038	0.039
150 mil 2 oz spear	2	160	0	0.115	0.019	0.239	0.041	0.044	0.053	0.117	2.900
150 mil 4 oz spear	2	160	0	0.050	0.001	0.011	0.040	0.042	0.045	0.057	0.080
150 mil 6 oz spear	2	160	0	0.050	0.001	0.012	0.039	0.040	0.044	0.057	0.119
150 mil 8 oz spear	2	160	0	0.047	0.001	0.009	0.038	0.040	0.045	0.051	0.089

This plot clearly shows that probe force and tip shape are the most important variables affecting probe to pad resistance, as would be expected, and the effects of the paste and reflow conditions are not particularly obvious. The mean resistances for the 4 oz and 6 oz probes were very similar in value. The spear probes had lower resistances than the blade probes; this seems counter-intuitive, since the spear probes would likely have to penetrate more flux residue pooled in the via depression than the blade probes. **Figure 5** shows a Minitab interaction plot for mean probe resistance against the same variables; again probe force and tip shape have the largest effect.

In order to get a better indication of the effects of paste and reflow, **Figures 6** and **8** show main effects plots for mean probe resistance against paste, reflow profile and number of reflows for 2 oz spear probes and 2 oz blade probes, respectively. Similarly, **Figures 7** and **9** show interaction plots for 2 oz spear probes and 2 oz blade probes, respectively. The more pin-testable Paste A and Paste B have lower mean resistances than Paste C, with its harder flux residue for both spear and blade probes. The effect of reflow, both profile and number of reflows, on flux probe-ability is not so straightforward; it is expected that solder paste flux would become more difficult to probe as it is exposed to increasing amounts of heat. For the pastes examined, the effect of reflow is very complex, and is different for blades and spears. Spears usually, but not always, had lower mean resistances when reflowed under cooler conditions than when reflowed with hotter conditions. However, when the interaction plot is considered, Paste B didn't follow this general trend for reflow profiles, and Paste A had lower mean resistance after two reflows than one. For blade probes, hotter reflows showed lower mean resistances than cooler reflows, and fluxes exposed to two reflows had lower mean resistances than that exposed to only one reflow.

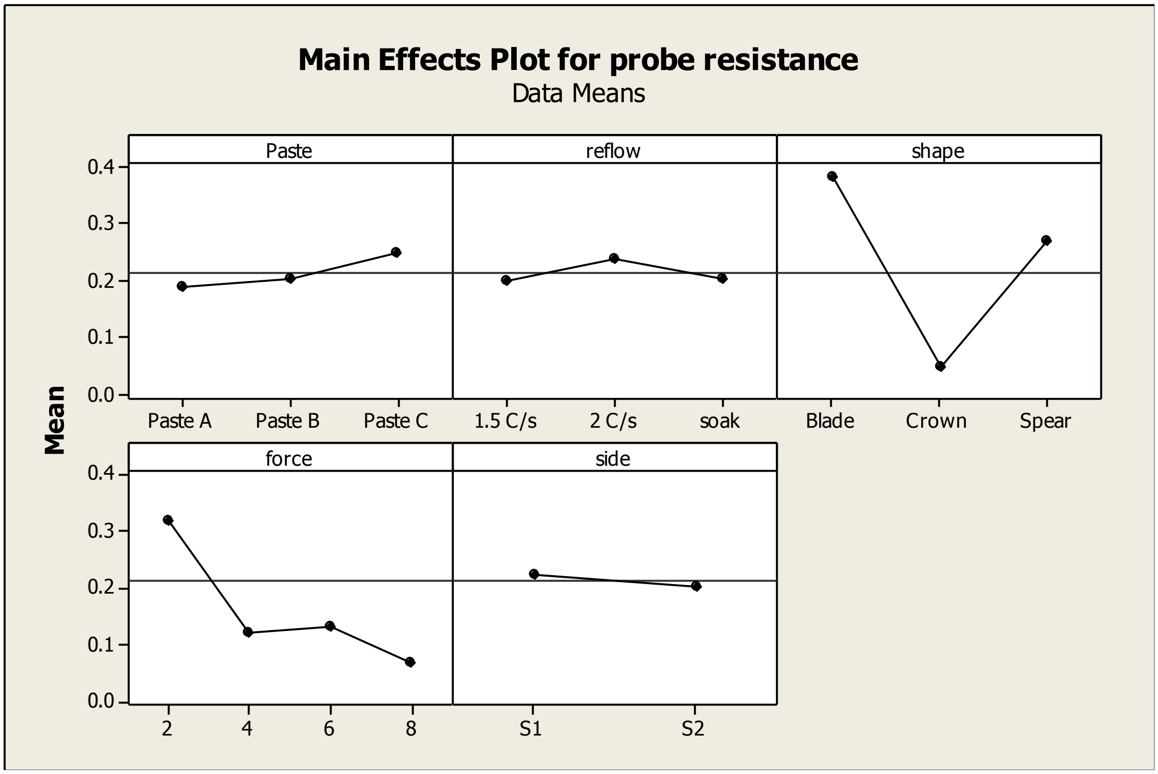

Figure 4. Main effects plot for probe resistance

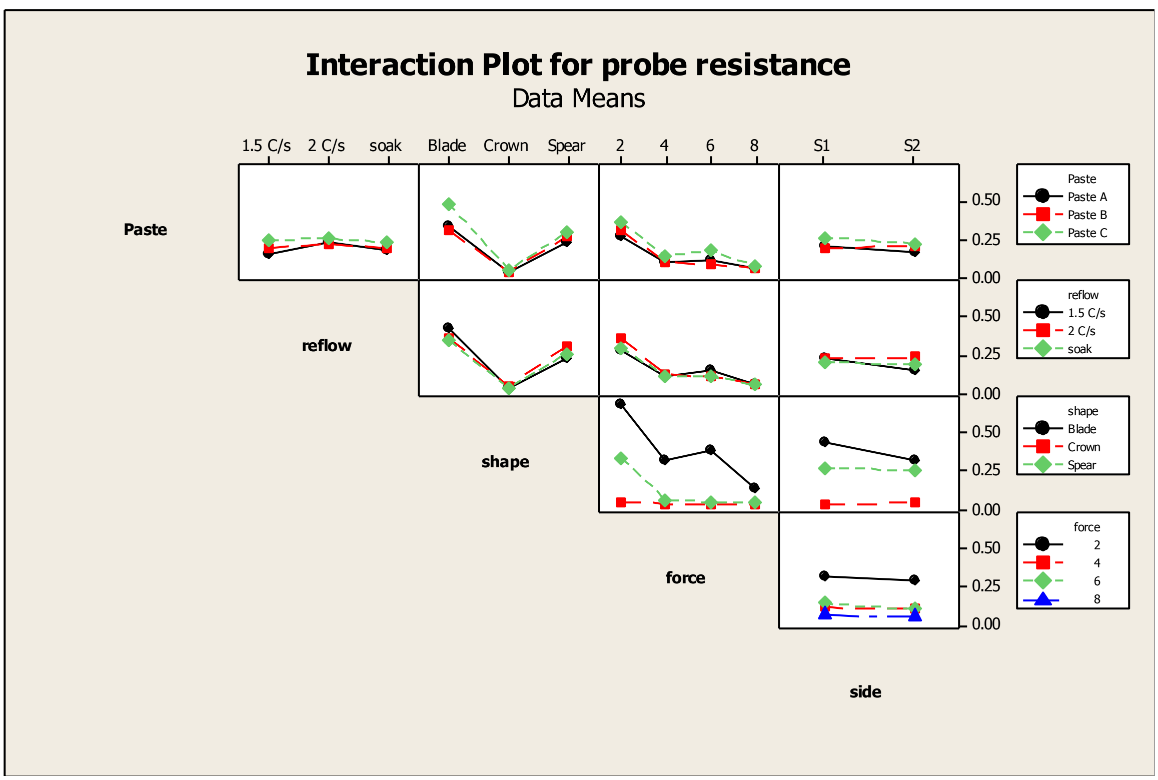

Figure 5. Interaction plot for probe resistance

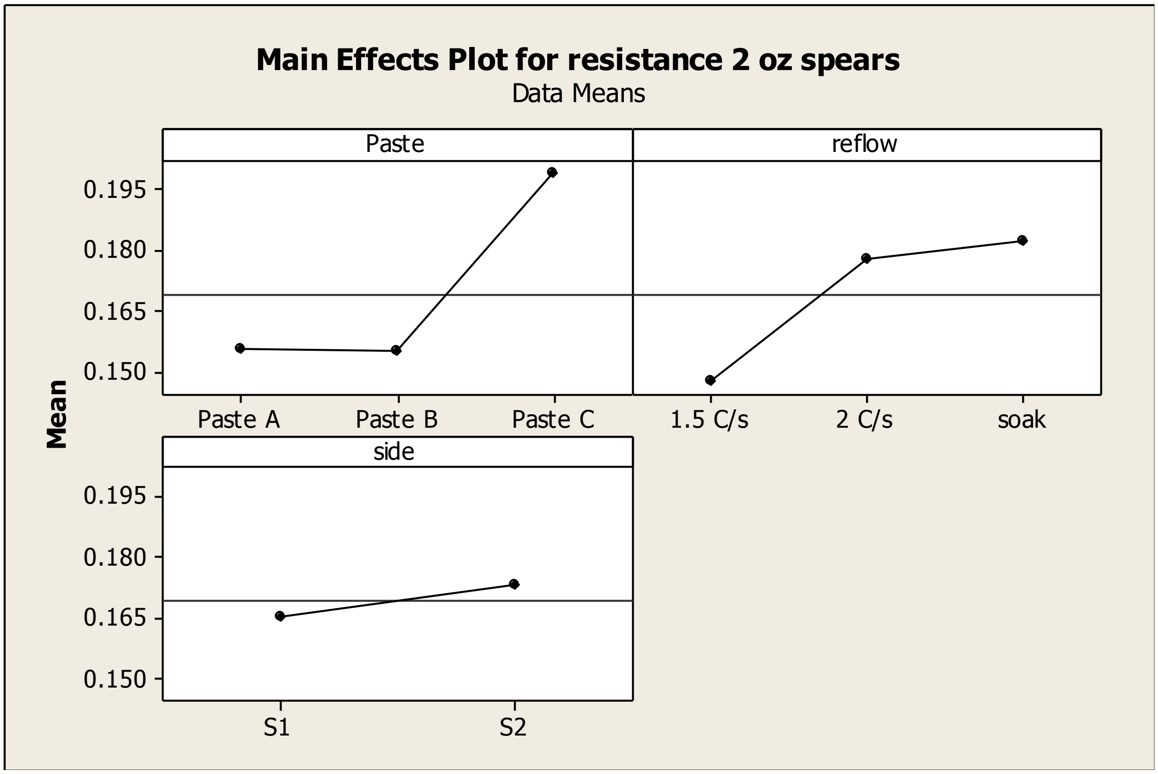

Figure 6. Main effects plot for probe resistance with 2 oz spear probes

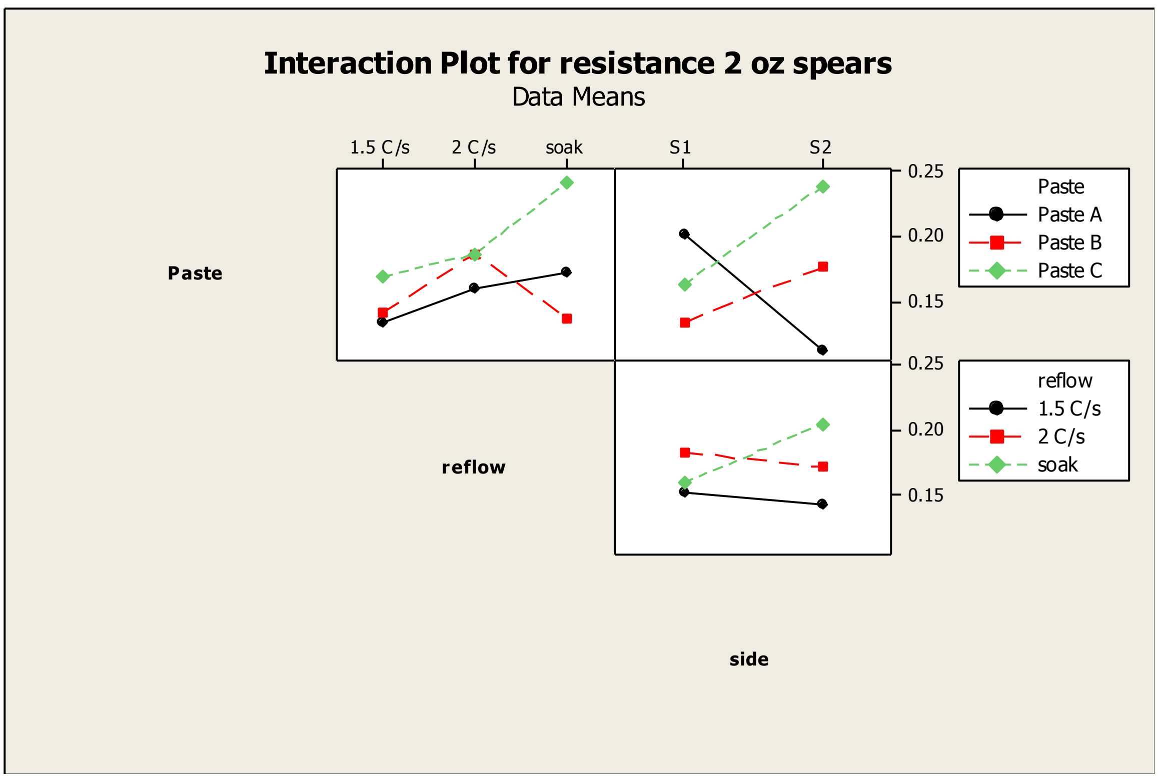

Figure 7. Interaction plot for probe resistance with 2 oz spear probes

Because the actual resistance of a particular probe is less important assembler's ICT test engineers than false non-continuous test results, the data from the nine paste/reflow profile combinations studied have been parsed into the percentage of open contacts (greater than 2000Ω), and contacts greater than 5Ω, 2Ω, 1Ω and 0.5Ω for the various types of probes studied. This sort of data is given in **Table 3,** again for Paste A reflowed using the 160˚C soak profile.

This ranked data was then further analyzed in Minitab to provide main effect and interaction plots for the variables paste, reflow profile, number of reflows, probe shape and probe force. A main effect plot for % open contacts against these variables is given in Figure **10.** With respect to % opens, while probe force still remains the most important influence, the solder paste used becomes as important as the probe tip shape. Pastes A and B clearly have fewer open contacts than Paste C. Reflow conditions still are less important than the other variables, though cooler reflow conditions give fewer opens than hotter ones. **Figure 11** give the interaction plot for the same variables, and shows the same trends. The main effects and interaction plots for % contacts

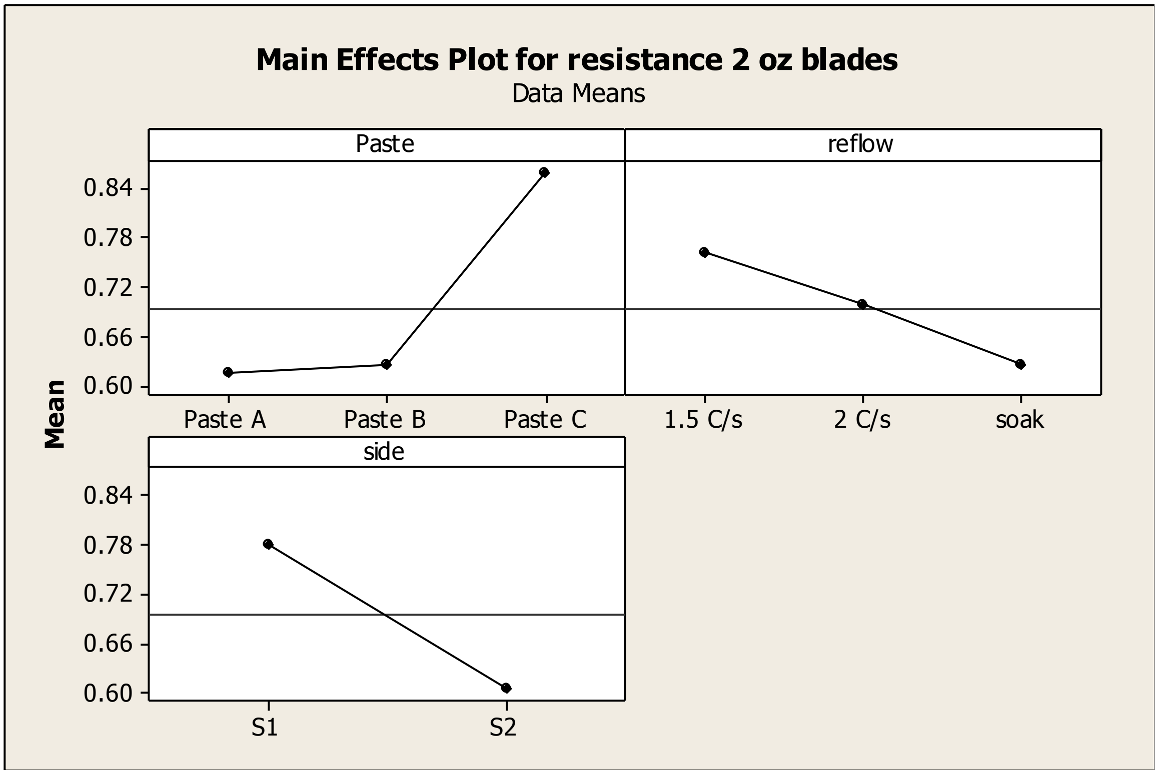

Figure 8. Main effects plot for probe resistance with 2 oz blade probes

Figure 9. Interaction plot for probe resistance with 2 oz blade probes

Table 3. % probe resistances values below certain low values

spacing mil	Shape	Force oz	Paste A 160 soak: one reflow % Open	one reflow <5 Ω	one reflow <2 Ω	one reflow <1 Ω	one reflow < 0.5 Ω	two reflows % Open	two reflows <5 Ω	two reflows <2 Ω	two reflows <1 Ω	two reflows < 0.5 Ω
40	Spear	2	0.0	0.1	2.4	5.4	13.5	0.0	0.2	0.8	2.9	7.3
75	Crown	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150	Blade	2	18.1	18.8	25.6	41.9	48.8	0.0	0.6	5.6	16.9	29.4
		4	1.3	1.3	5.0	10.0	16.9	0.0	0.0	0.0	3.8	11.3
		6	0.0	0.0	0.6	16.3	21.3	0.0	0.0	1.3	13.8	21.9
		8	0.0	0.0	0.0	1.3	3.1	0.0	0.0	0.0	0.0	1.9
	Crown	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spear	2	12.5	12.5	13.8	16.3	20.6	0.0	0.0	0.6	0.6	1.3
		4	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Open is >2000 Ω

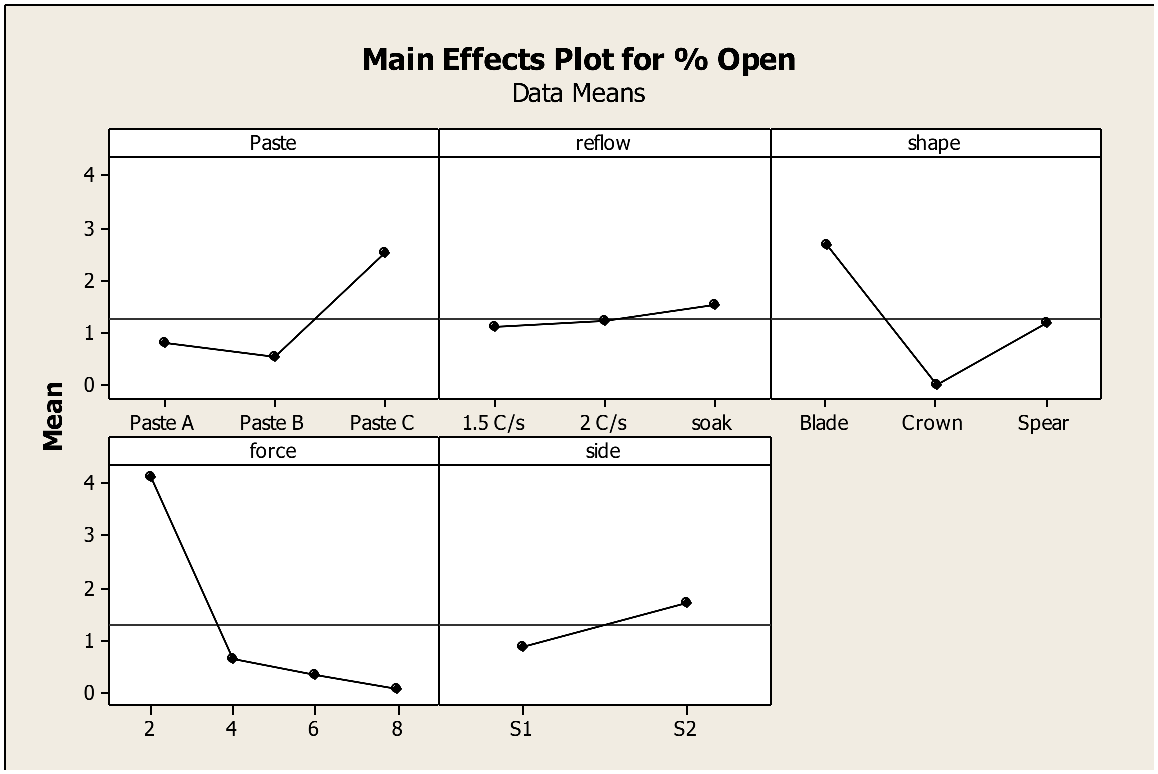

Figure 10. Main effects plot for % open contacts (R>2000Ω)

greater than 5Ω are nearly the same as those obtained for open contacts; very few contacts are between 5 and 2000Ω. Some assemblers' use 5Ω as a limit for continuity determinations, and so individual probe contacts of less than 1Ω would be needed. **Figure 12** and **13** the main effects and interaction plots, respectively, for % contacts greater than 1Ω against the variables paste, reflow profile, number of reflows, probe shape and probe force. Here the plots are between those for % open and mean resistance. Figures 14 and 15 show main effects plots % opens and % >1Ω for all 2 oz probes against the variables paste, reflow profile, number of reflows, and probe shape. For the % open plot, the effect of reflow conditions, profile and number, are obvious and % opens increase with the heat the flux residue is exposed to, as is expected. The plot for %> 1Ω does not show any strong influence of reflow conditions.

Figure 11. Interaction plot for % open contacts (R>2000Ω)

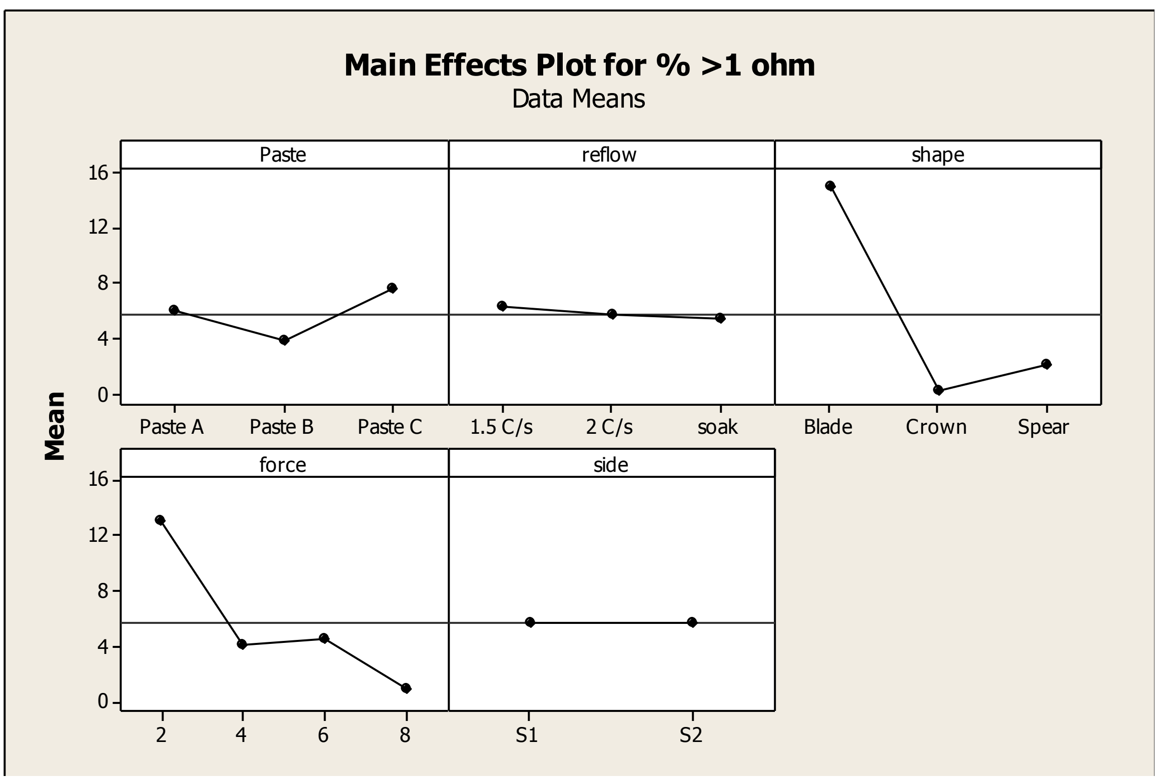

Figure 12. Main effects plot for % >1 ohm

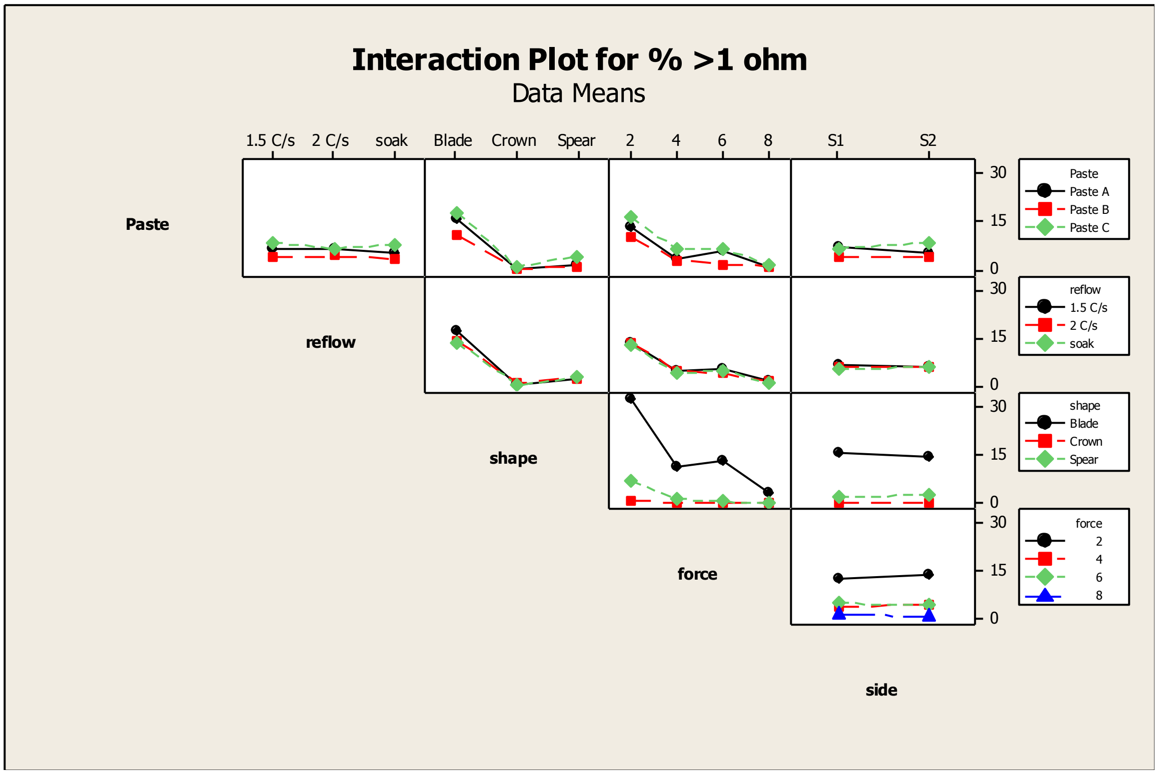

Figure 13. Interaction plot for % >1 ohm

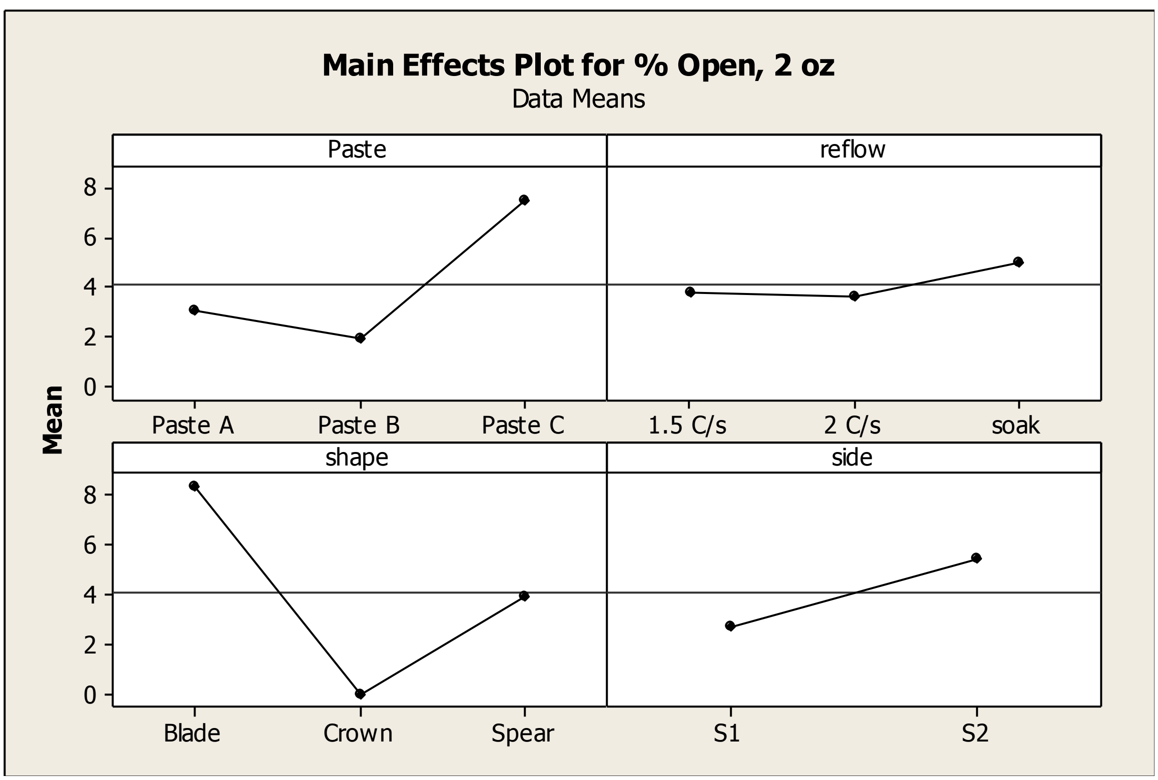

Figure 14. Main effects plot for % open, 2 oz probes

Figures 16 and **17** show main effect plots for % open and % >1Ω, respectively, for 2 oz spears against paste and reflow conditions, and **Figures 18** and **19** show the corresponding interaction plots. For % opens and % >1Ω using 2 oz spears, Paste B is the most pin-testable, closely followed by Paste A, and Paste C is the least pin-testable. The effect of reflow conditions for both % opens and % >1Ω shows that the flux residues tend to get harder to penetrate as the residue is exposed to more heat. Since more solvents and softening agents are driven off by heat, this effect would be expected.

The interaction plots indicate that the decrease of pin-testability with heat exposure is followed mostly by Pastes A and C, and Paste B, with the most penetrable residue are the least affected by heat. The penetrability of Paste A, while better with cooler reflow profiles, is more penetrable after a second reflow.

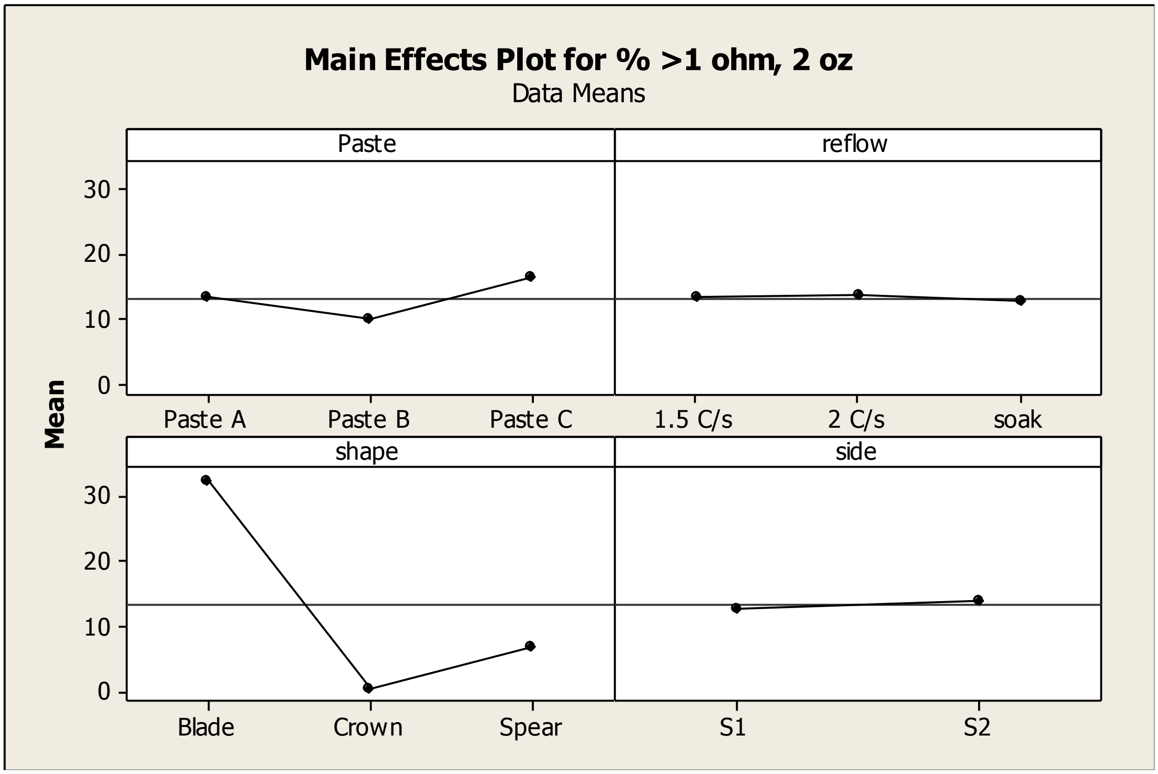

Figure 15. Main effects plot for % >1 ohm, 2 oz probes

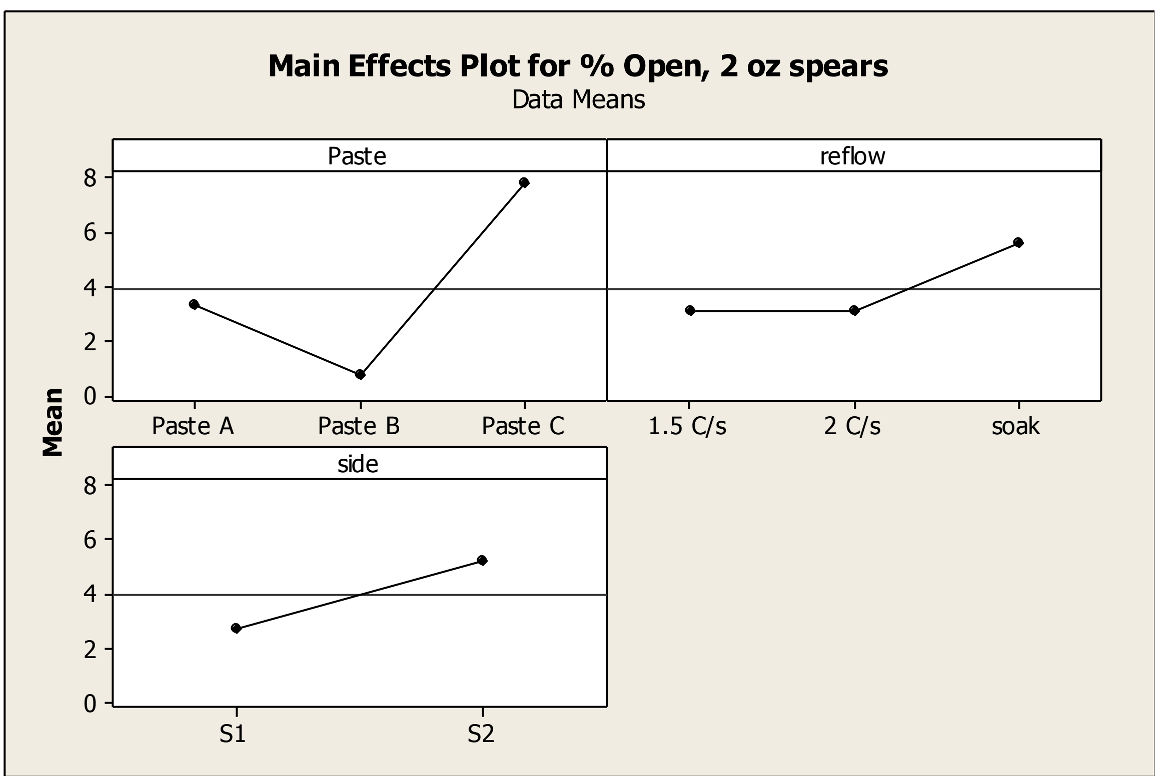

Figure 16. Main effects plot for % open, 2 oz spear probes

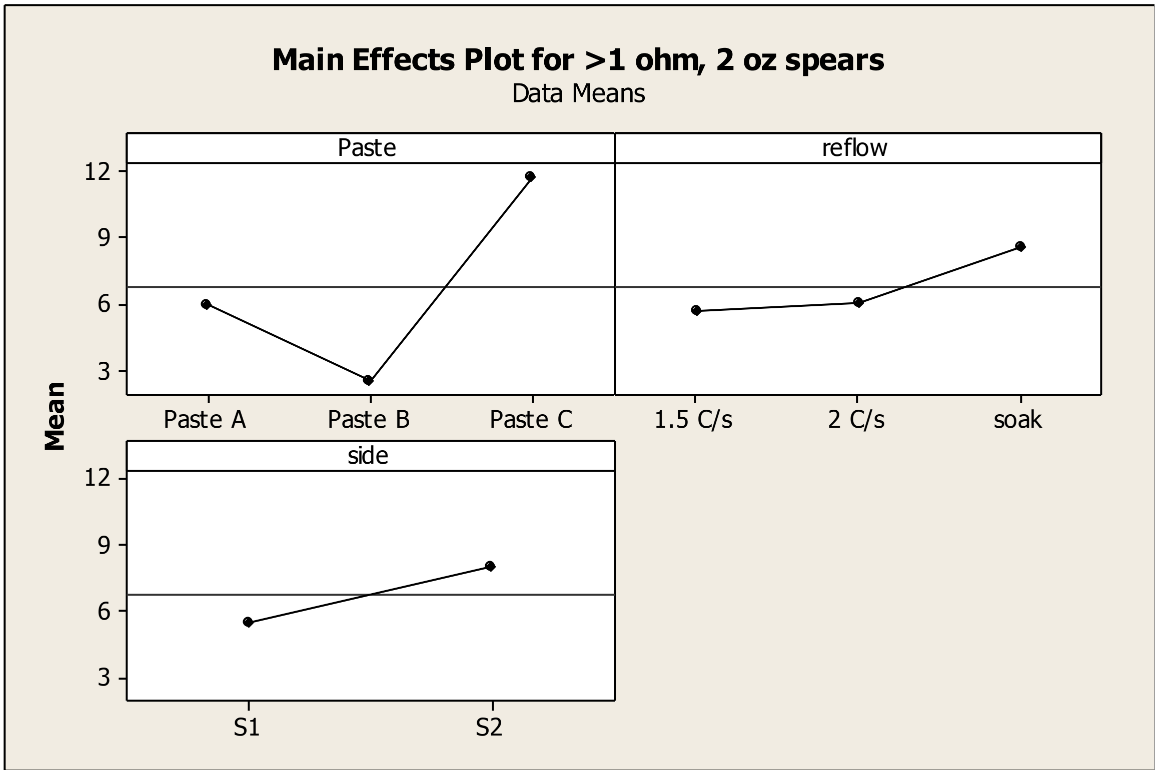

Figure 17. Main effects plot for % 1 ohm, 2 oz spear probes

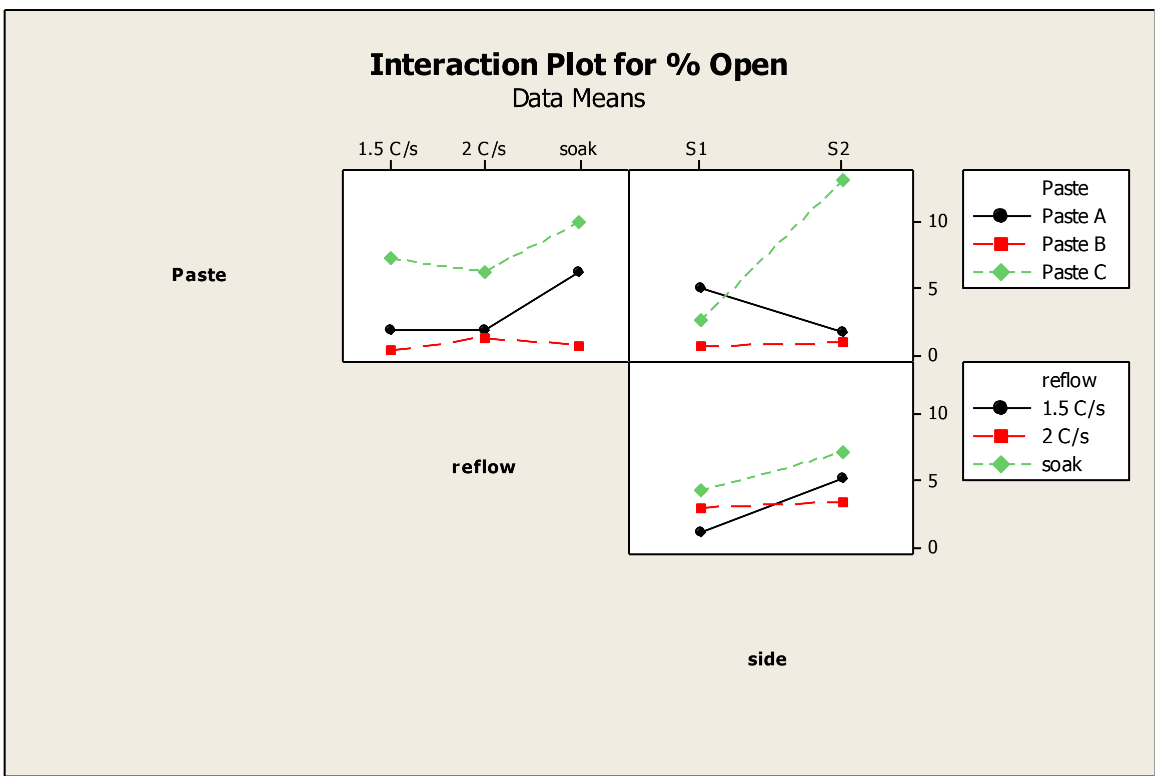

Figure 18. Interaction plot for % open, 2 oz spear probes

Figures 20 and **21** show main effect plots for % open and % >1Ω, respectively, for 2 oz blades against paste and reflow conditions, and **Figures 22** and **23** show the corresponding interaction plots. Here the plots for % opens and % >1Ω are not as similar as they were for spear probes. Paste A has nearly as many resistance values greater than 1Ω as the less pin-testable Paste C, and the effect of reflow conditions are complicated, as they were for the mean resistance plots for blade probes.

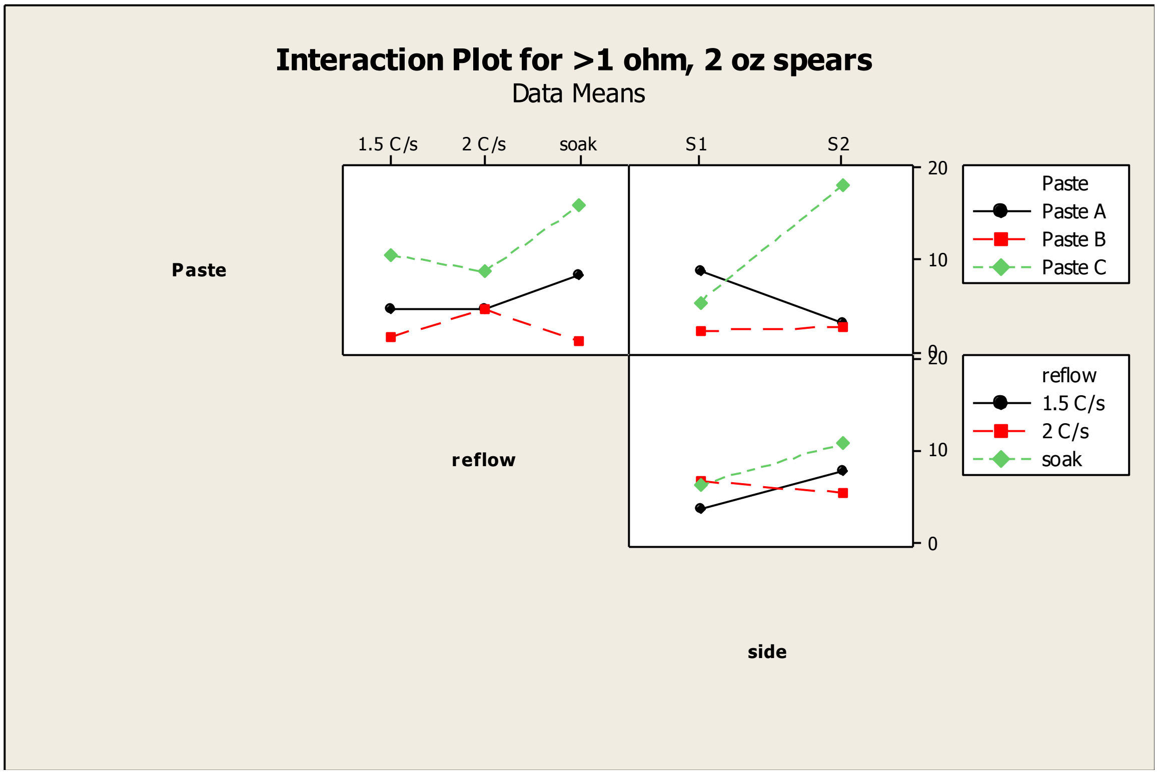

Figure 19. Interaction plot for % 1 ohm, 2 oz spear probes

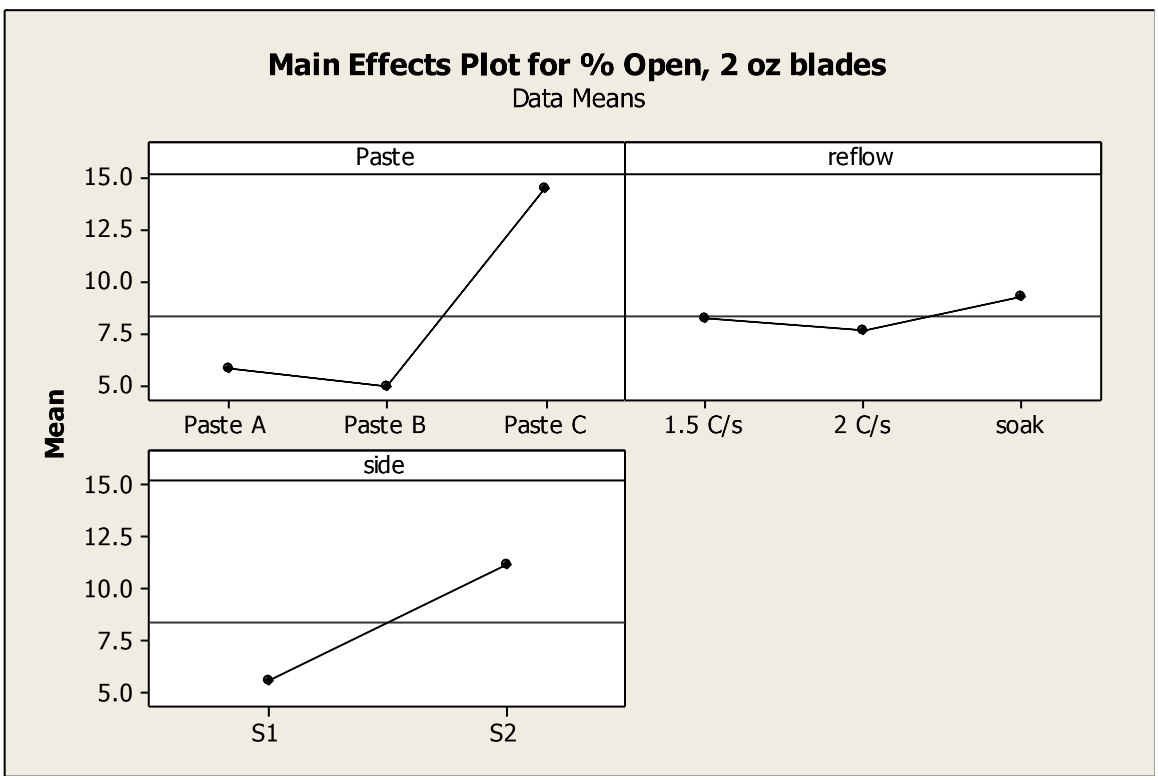

Figure 20. Main effects plot for % open, 2 oz blade probes

In general, the pin-testability information obtained with this new method is richer, but more complicated than that obtained with the older, single probe method.

While some solder pastes are easier to probe than others, some solder pastes are probed more effectively with spear probes and others with blade probes. The effect of reflow conditions on flux probability may also be complex, and may vary with solder pastes and probe types.

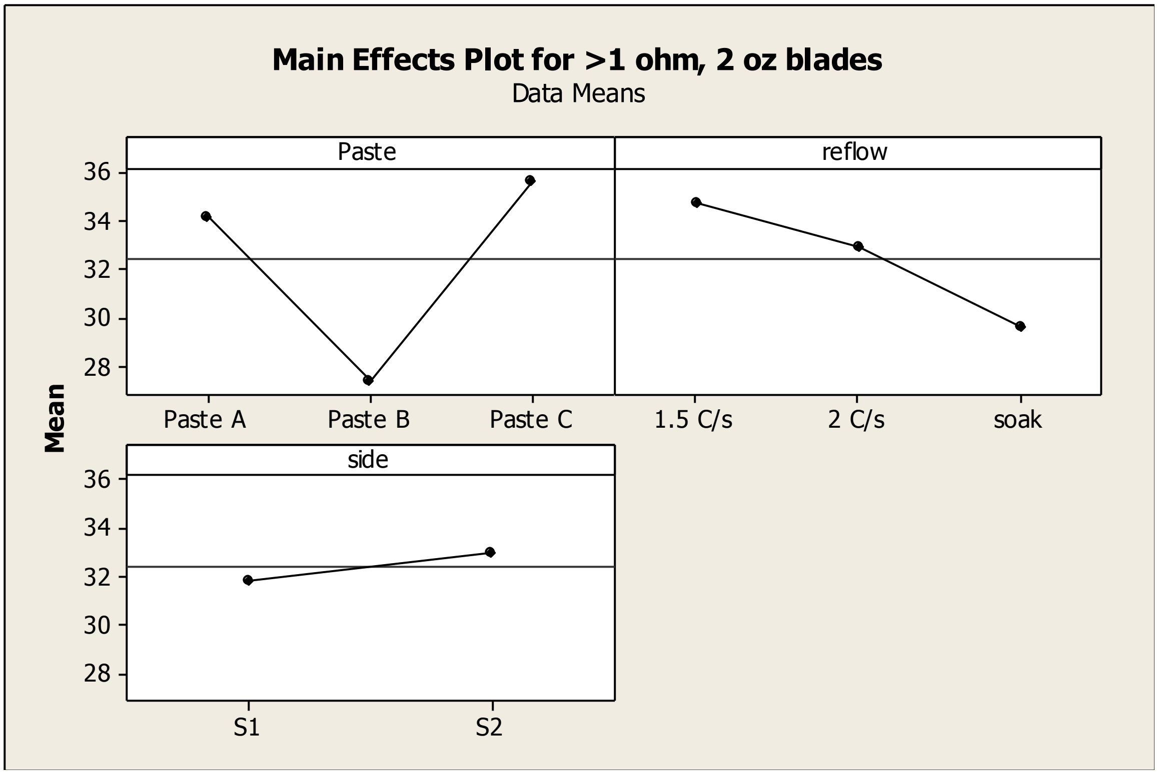

Figure 21. Main effects plot for % 1 ohm, 2 oz blade probes

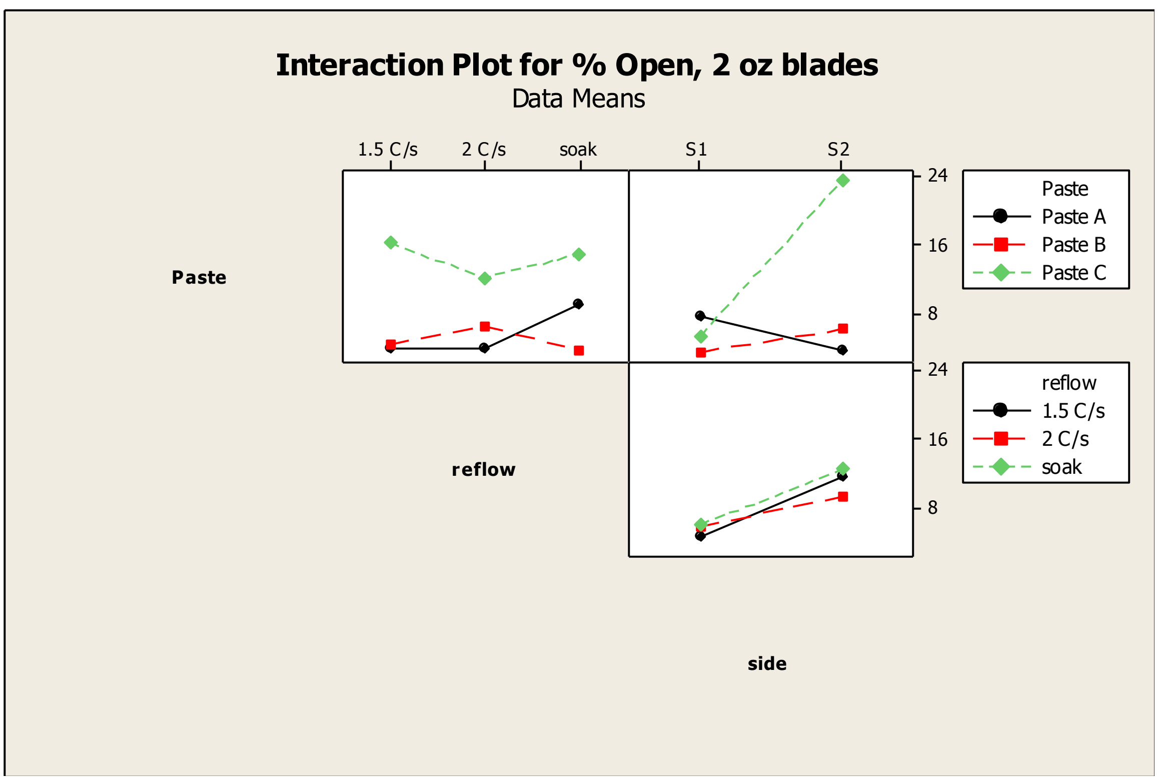

Figure 22. Interaction plot for % open, 2 oz blade probes

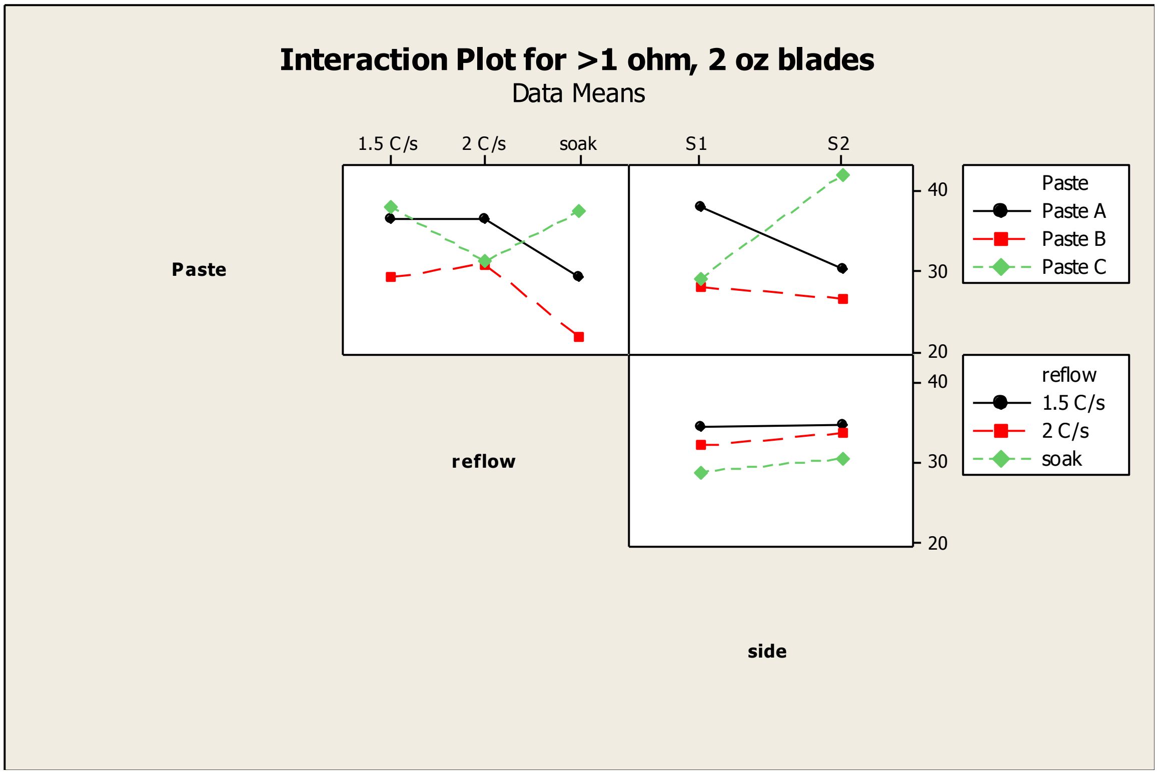

Figure 23. Interaction plot for % 1 ohm, 2 oz blade probes

Conclusions

This new method for evaluating solder paste flux ICT probability provides more informative data than our older Camelot dispenser "flying probe" method. Different probe tip shapes and forces are used during the same evaluation, providing information about the optimal probe type to use with a particular flux residue. The method also more closely resembles that used by circuit assemblers to test production circuit boards, by using a vacuum actuated ICT fixture. While the probes are the most important factors with regard to probe resistance and non-contacts, the effect of solder paste type and reflow conditions can be determined, especially for probes with smaller forces. These effects are often complicated, and may indicate why the single probe method did not predict flux probe-ability by circuit board assemblers.

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