SOLDER FLOW OVER FINE LINE PWB SURFACE FINISHES

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ABSTRACT

The rapid advancement of interconnect technology has stimulated the development of alternative printed wiring board (PWB) surface finishes to enhance the solderability of standard copper and solder-coated surfaces. These new finishes are based on either metallic or organic chemistries. As part of an ongoing solderability study, Sandia National Laboratories has investigated the solder flow behavior of two azole-based organic solderability preservatives, immersion Au, immersion Ag, electroless Pd, and electroless Pd/Ni on fine line copper features. The coated substrates were solder tested in the as-fabricated and environmentally-stressed conditions. Samples were processed through an inerted reflow machine. The azole-based coatings generally provided the most effective protection after aging. Thin Pd over Cu yielded the best wetting results of the metallic coatings, with complete dissolution of the Pd overcoat and wetting of the underlying Cu by the flowing solder. Limited wetting was measured on the thicker Pd and Pd over Ni finishes, which were not completely dissolved by the molten solder. The immersion Au and Ag finishes yielded the lowest wetted lengths, respectively. These general differences in solderability were directly attributed to the type of surface finish which the solder came in contact with. The effects of circuit geometry, surface finish, stressing, and solder processing conditions are discussed.*

Keywords: surface finish, fine line features, solder flow, environmental stressing

INTRODUCTION

Aging of PWB Cu surfaces, whether under ambient or thermally induced conditions, can be detrimental to soldering during subsequent assembly processing. To alleviate the problem and meet the demanding requirements imposed by advanced interconnect technology, alternative surface finishes are being applied as a protective overcoat to Cu[1-3]. These finishes are based on metallic or organic chemistries that maintain or enhance solderability of the underlying Cu surface. The ability of the new finishes to promote solder flow on fine line PWB features is of particular relevance for both commercial and military applications.

Copper conductor paths, common to most PWB's, inherently possess some degree of surface capillarity and can be sensitive to the environmental conditions. The effort to maximize PWB real estate, by increasing circuit density through finer pitch size, will certainly create additional solderability problems of the smaller Cu features, since a potentially larger percentage of unwet surface area can result. Protective metallic and organic finishes should assure meeting these growing requirements for solder processing, even after exposure to abnormal temperature and humidity environments.

An investigation was conducted recently by Sandia National Laboratories and other industrial researchers to evaluate the solder flow behavior of several leading surface finish candidates. They included two azole-based organic solderability preservatives (OSP's), immersion Au, immersion Ag, electroless Pd, and electroless Pd/Ni. The finishes were applied directly to a Cu test pattern. Eutectic Sn-Pb solder was reflowed on the as-fabricated and environmentally-stressed surfaces.

The test substrate was based on a surface capillary flow test vehicle that was developed for the National Center for Manufacturing Sciences (NCMS) PWB Interconnect Systems Surface Finishes effort[4-6]. The test geometry (Fig. 1) consists of a fixed circular pad with an attached strip whose line width can be varied to control solder flow down the strip. This line width-to-pad radius ratio is a critical parameter in determining flow behavior, in conjunction with the chemical reaction that occurs at the liquid solder and surface finish interface. Previous work suggests that a 0.75 ratio yields a sufficient condition for consistent solder flow. In this study, the 0.75 ratio was used as the standard condition for comparing flow data.

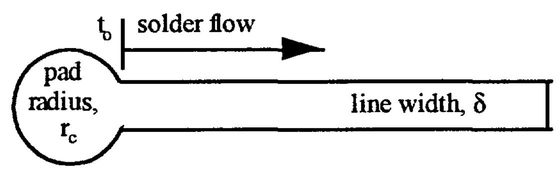

Figure 1: Solder capillary flow from the circular pad along the connected strip depends on the ratio of line width to pad radius (δ/r_c).

Four different environmental stressing conditions were evaluated. They included an accelerated storage environment, an air bake, an intermediate temperature/humidity exposure, and a simulated first pass reflow treatment. The following sections describe the solder flow results for the selected surface finishes. The results clearly demonstrate the importance of stressing and interfacial reactions on solder wetting and flow.

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MATERIALS & EXPERIMENTAL PROCEDURE

The solder flow test vehicle was fabricated with conventional PWB materials and based on a single-sided, 0.060" (1.52 mm) thick, epoxy resin/fiberglass-reinforced laminate (FR-4). The layout design consisted of 0.010, 0.020, 0.030, and 0.040 inch (0.25, 0.51, 0.76, and 1.02 mm) wide copper lines attached to a 0.080" (2.03 mm) diameter pad (Fig. 2). The resulting line width-to-pad radius ratios (δ/r_C) were 0.25, 0.5, 0.75, and 1.0. The 30 mil line was used as the baseline test condition, where $\delta/r_C = 0.75$. The line length, or maximum possible flow, was 1.5" (38.1 mm). The copper patterns (0.5 oz.) were imaged and etched per the described geometry. Additional copper was electrodeposited on the vendor-etched Cu to a final thickness of 35 µm (1 oz. Cu). The organic and metallic surface finishes were applied to these copper features by different vendors. The finishes and their thickness are listed in Table 1.

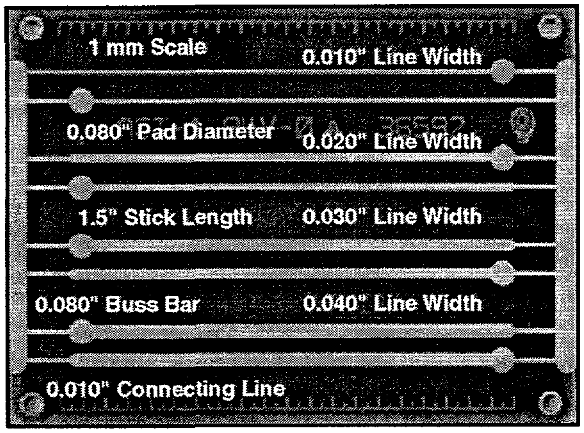


Figure 2: Solder flow test vehicle with four different "δ to r_c" patterns.

Solder flow experiments were conducted with eutectic 63Sn-37Pb (wt. %) solder pellets. The nominal pellet weight was 10.3 mg ± 0.1. A single pellet was placed on each test pad after being dipped in flux. Test coupons were coated with rosin (R), rosin mildly activated (RMA), or low solids (LS) flux prior to solder testing. The R and RMA fluxes were normalized to a solids content of 25% (vol. %). The LS flux contained 2-3% solids.

Test substrates were not given any special precleaning treatment before assembly. Solder flow tests were conducted with a tabletop reflow machine under an inerted nitrogen cover. The machine consists of four conduction heating zones, which were adjusted for the recommended preheat, peak temperature, time above melting, heating rate, and cooldown conditions. The nominal profile settings were 100°C-150°C-250°C-120°C at a travel speed of 7 inch/min. (3 mm/s). The heating rate was approximately 1.0°C/s, with the time spent above 190°C at 30-40 seconds. The measured topside peak temperature was 210-215°C. The hot zone was covered and fully inerted with technical grade nitrogen at a flow rate of 30 SCFH (2.4 x 10^{-4} m^3/s). The test coupons were processed through the machine with the smaller test lines at the sample front and perpendicular to the line of travel.

Table 1: Surface Finishes Over Cu PWB Features

Surface Finish	ID	Average Thickness
Imidazole OSP	IMD	50-75 Å (thin)
Benzimidazole OSP	BIMD	3000-5000 Å (thick)
Immersion Au over Electroless Ni	Au/Ni	5-10 µin. 200 µin.
Immersion Ag	Ag	2-4 µin.
Electroless Pd, thin	TnPd	8-10 µin.
Electroless Pd over Electroless Ni	TnPd/Ni	8-10 µin. 150 µin.
Electroless Pd, thick	TkPd	20-25 µin.
Electroless Pd over Electroless Ni	TkPd/Ni	20-25 µin. 150 µin.

Reflow experiments were performed on as-fabricated and environmentally stressed samples. Four stressing conditions were evaluated:

(a) flowing mixed gas (FMG) Class II accelerated aging environment (35°C at 70% relative humidity in an atmosphere containing 10 ppb H_2S, 10 ppb Cl_2, and 200 ppb NO_2); the length of exposure was for 96 hours, empirically equivalent to a 3 year storage in a typical indoor industrial environment; the dominant failure mechanism is exposure of the underlying Cu or Ni layer due to pores in the protective overcoat.
(b) temperature/humidity stressing at 50°C and 90% relative humidity for 24 hours.
(c) air bake at 110°C for 8 hours.
(d) simulated, single pass reflow cycle before solder testing, using the thermal profile described above (100°C-150°C-250°C-120°C at 7 inch/min. in 30 SCFH nitrogen).

The four stressing conditions were representative of typical thermal storage and processing conditions that a PWB might see before assembly soldering. The test substrates were aged according to the described stressing conditions and solder tested within 24 hours of aging. Stressing was not performed if the baseline, as-fabricated solder flow results were poor for any of the surface finish or flux conditions.

Three replicates were processed per test condition for the OSP, Au, and Ag surface finishes, or a total of six solder flow measurements per test line geometry. The availability of Pd and Pd/Ni substrates was limited, so only two replicates, or four test lines, were processed for these finishes. After reflow soldering, flux residues were removed ultrasonically by cleaning with trichloroethylene and isopropyl alcohol. The wetted length of solder on the 30 mil test line was then measured from the edge of the pad to the tip of the solder on the attached lines. The 30 mil results were used as the standard reference for comparing the different surface finishes and test conditions. Selected samples were also cross-sectioned for subsequent metallographic analysis to determine the interfacial reactions between the reflowed solder and surface finishes.

RESULTS AND DISCUSSION

Measured wetting results are summarized in Tables 2-6. Flow data is presented for the 30 mil test lines. The data represents the average length that the reflowed solder wet the attached lines, ± one standard deviation. The results are tabulated according to surface condition (i.e., as-fabricated or environmentally stressed).

Table 2: Wetted Distance of Solder Along As-Fabricated 30 Mil Test Lines with Different Surface Finishes

Surface Finish (Over Cu)	Flux Type	Wetted Distance (mm)	± One Standard Deviation
TnPd	R	1.8	0.4
	RMA	15.8	2.3
	LS	0.8	0.4
TnPd/Ni	R	1.0	0.0
	RMA	7.1	0.3
	LS	0.5	0.7
TkPd	R	1.5	0.0
	RMA	8.0	1.5
	LS	0.3	0.4
TkPd/Ni	R	1.0	0.0
	RMA	9.6	1.8
	LS	0.8	1.1
Ag	R	1.4	0.3
	RMA	1.8	0.3
	LS	1.0	0.0
Au/Ni	R	2.9	0.3
	RMA	3.9	0.3
	LS	1.5	0.0
IMD	R	22.3	2.1
	RMA	33.0	2.2
	LS	1.6	0.9
BIMD	R	30.4	7.4
	RMA	35.2	0.6
	LS	3.3	0.9

Table 3: Wetted Distance of Solder Along FMG/Class II Aged (96 hrs.), 30 Mil Test Lines

Surface Finish (Over Cu)	Flux Type	Wetted Distance (mm)	± One Standard Deviation
TnPd	RMA	3.3	0.3
TnPd/Ni	RMA	1.6	0.3
TkPd	RMA	2.1	0.5
TkPd/Ni	RMA	1.9	0.3
Ag	R	1.0	0.0
	RMA	1.0	0.0
Au/Ni	R	2.5	0.0
	RMA	3.0	1.1
IMD	R	23.1	5.9
	RMA	24.0	1.0
	LS	1.6	1.0
BIMD	R	28.6	2.7
	RMA	34.0	2.8
	LS	4.3	0.7

Table 4: Wetted Distance of Solder Along 50°C/90%RH Aged (24 hrs.), 30 Mil Test Lines

Surface Finish (Over Cu)	Flux Type	Wetted Distance (mm)	± One Standard Deviation
TnPd	RMA	22.3	2.5
TnPd/Ni	RMA	3.6	0.5
TkPd	RMA	7.6	2.7
TkPd/Ni	RMA	5.6	0.9
Ag	RMA	1.1	0.3
Au/Ni	RMA	3.0	0.0
IMD	R	19.8	5.3
	RMA	36.5	0.6
BIMD	R	20.5	2.1
	RMA	36.5	0.7

Table 5: Wetted Distance of Solder Along Air Baked (110°C for 8 hrs.), 30 Mil Test Lines

Surface Finish (Over Cu)	Flux Type	Wetted Distance (mm)	± One Standard Deviation
TnPd	RMA	15.3	3.9
TnPd/Ni	RMA	5.4	1.0
TkPd	RMA	9.3	2.4
TkPd/Ni	RMA	8.8	2.1
Ag	RMA	2.5	1.5
Au/Ni	RMA	3.5	0.4
IMD	R	30.1	1.5
	RMA	32.5	3.7
BIMD	R	31.5	1.0
	RMA	34.7	1.1

Table 6: Wetted Distance of Solder Along Simulated Nitrogen Reflowed, 30 Mil Test Lines

Surface Finish (Over Cu)	Flux Type	Wetted Distance (mm)	± One Standard Deviation
TnPd	RMA	20.5	3.4
TnPd/Ni	RMA	4.8	1.2
TkPd	RMA	8.8	1.9
TkPd/Ni	RMA	5.6	1.8
Ag	RMA	1.3	0.3
Au/Ni	RMA	3.9	0.6
IMD	R	20.3	4.6
	RMA	28.6	3.1
BIMD	R	31.0	2.0
	RMA	32.0	1.4

The baseline flow results were most consistent for the RMA flux, particularly on the OSP surface finishes (see Fig. 3). The OSP's also exhibited good wetting with the R-type flux. The BIMD OSP was less sensitive to the flux chemistry, with excellent solder flow for both rosin-based formulations. Maximum BIMD solder flow was, in most cases, to the end of the 30 mil test line.

The baseline Pd, Ag, and Au surface finishes generally yielded poor solder flow with the R flux. Moderate wetting was observed on the Pd finishes, reflowed with the RMA flux. The wetted distances ranged from 7 to 16 mm, depending on the primary finish thickness and the presence of the intermediate Ni underlayer. Of the metallic coatings, the thin Pd finish yielded the best wetting results.

Poor solder flow was obtained with the LS flux for all tested surface finishes, including the OSP's. The results are consistent for the narrow processing window and higher surface energies associated with LS fluxes. The reflow profile was not optimized for this condition.

As part of the baseline evaluation, representative reflow samples were selected for cross-sectioning and microstructural analysis. Typical interfacial reactions with the 63Sn-37Pb solder for the Pd and Pd/Ni surface finishes are shown in Figs. 4a-d. The molten solder dissolves the relatively thin, primary metallic overcoat (Ag, Au, or Pd), and forms the Cu_6Sn_5 intermetallic compound at the Cu-solder interface or Ni_3Sn_4 intermetallic at the Ni-solder interface.

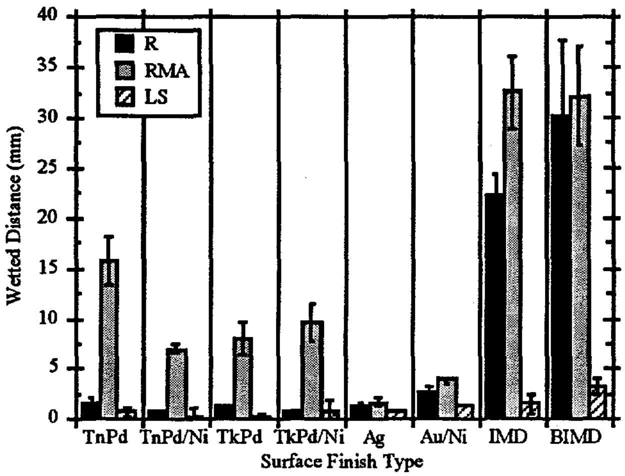
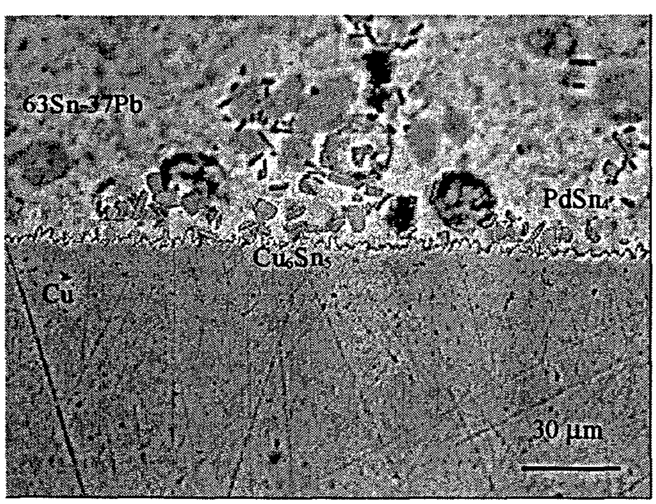
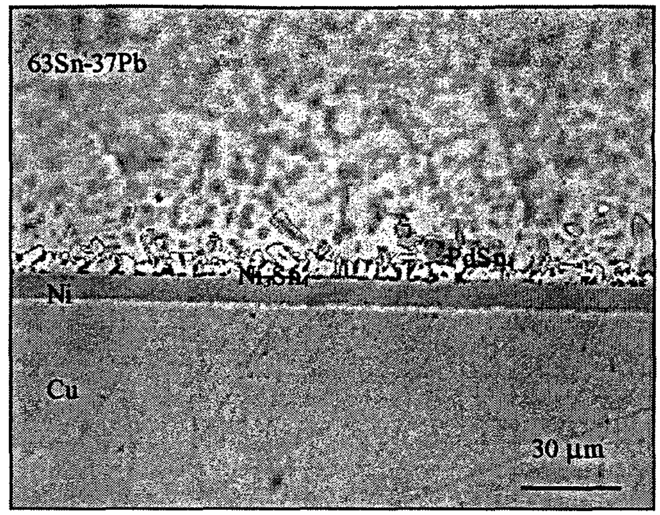


Figure 3: Baseline (as-fabricated) solder flow results on the different surface finishes for the 30 mil test line.

Ag_3Sn, $AuSn_4$, or $PdSn_4$ intermetallic precipitates are also found in the bulk solder, typically near the reaction interface, with the precipitate concentration dependent on solute solubility and the amount of Ag, Au, or Pd dissolved by the liquid solder. The change in intermetallic concentration can be seen in Figs. 4a vs. 4c and Figs. 4b vs. 4d, where the volume of $PdSn_4$ in the solder increased as the initial Pd finish thickness was increased. This increasing concentration directly affected the wetted distance on the test line. Solder flow generally decreased as the $PdSn_4$ precipitates increased. This is shown in Fig. 3, where the thinner Pd over Cu finish exhibited better solder flow than the thicker Pd finish, approx. 16 vs. 8 mm, respectively. The lower wetting value was attributed to an increase in solder viscosity.



(a)



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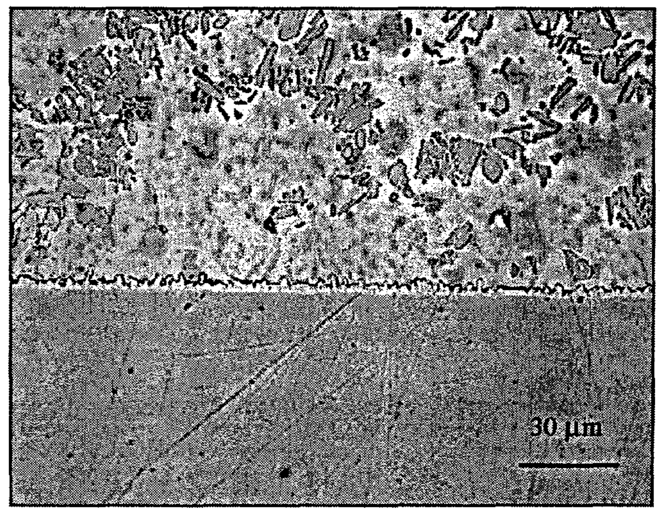

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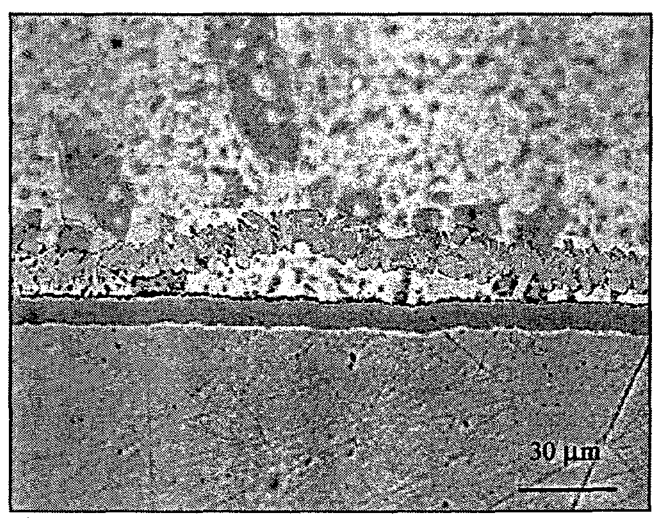

(d)

Figure 4: Optical images of cross-sectioned, baseline samples reflowed with 63Sn-37Pb solder on (a) thin Pd over Cu, (b) thin Pd over Ni/Cu, (c) thick Pd over Cu, and (d) thick Pd over Ni/Cu surface finishes.

After establishing the baseline solder flow conditions, the aging/stressing tests were conducted. The solder flow results on these samples with RMA flux are summarized in Figs. 5-8.

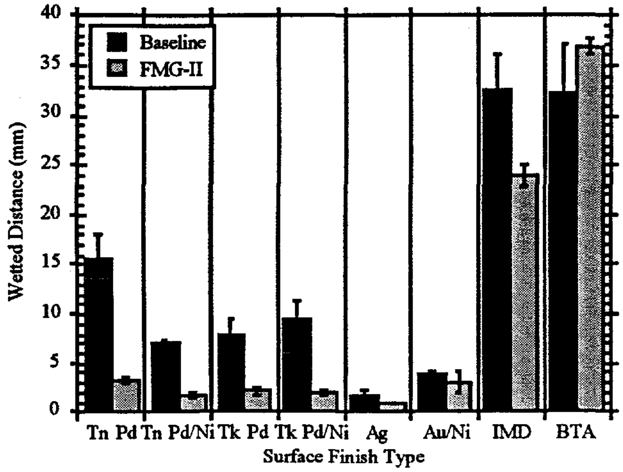

Figure 5: Solder flow comparison of baseline (as-fabricated) vs. FMG/Class II aged (simulated 3 yr.) 30 mil test lines, with different surface finishes. Reflow tests conducted with RMA flux.

The simulated, 3 year storage condition (FMG Class II for 96 hrs.) degraded solder flow, particularly on the Pd finishes (compare Baseline vs. FMG-II test results shown in Fig. 5). The IMD-coated substrates experienced a 10 mm decrease in flow after aging, although the resulting 24 mm wetted distance was still substantially higher than the distance wet on the untreated, baseline metallic coatings.

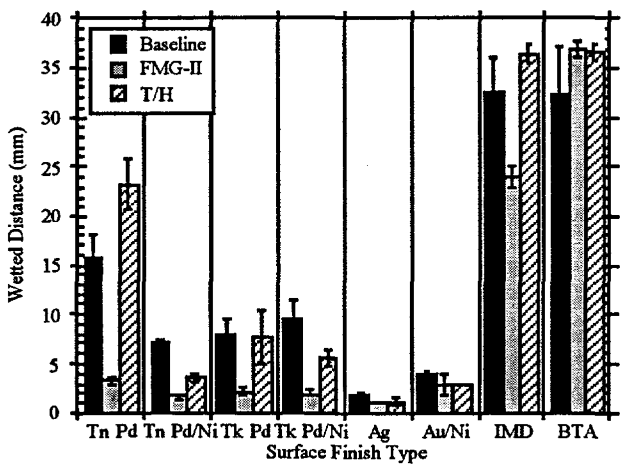

Figure 6: Solder flow comparison of baseline vs. FMG/Class II and 50°C at 90% RH (T/H for 24 hrs.) aged 30 mil test lines, for different surface finishes. Solder tests conducted with RMA flux.

The effect of extended moderate temperature and humidity exposure was considered next. In general, test coupons aged at 50°C and 90% relative humidity for 24 hours (T/H) did not exhibit any significant decrease in wetting from the baseline condition. The TnPd finish even showed some evidence of improved solder flow. Fig. 6 compares the wetted distances on the 30 mil test lines for the baseline, FMG/Class II and T/H aged specimens. The FMG/Class II exposure clearly had the greatest impact to solder flow degradation, even when compared with the 110°C air baked and nitrogen single pass, reflowed samples (Fig. 7-8). The air baked and reflowed samples, tested with RMA flux, behaved very similar to the baseline condition.

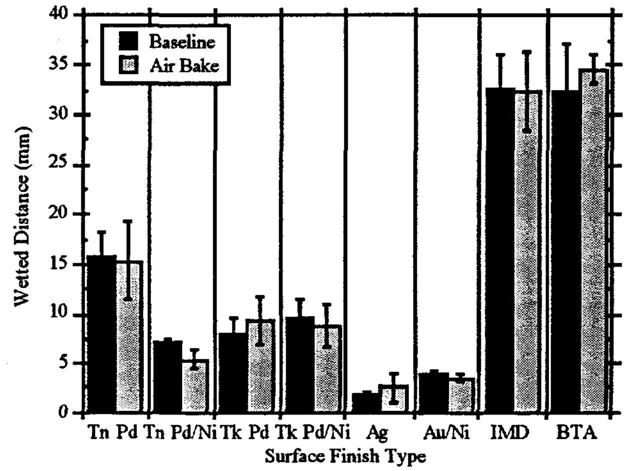

Figure 7: Solder flow comparison of baseline vs. 110°C air baked (8 hrs.) 30 mil test lines, for different surface finishes. Solder tests conducted with RMA flux.

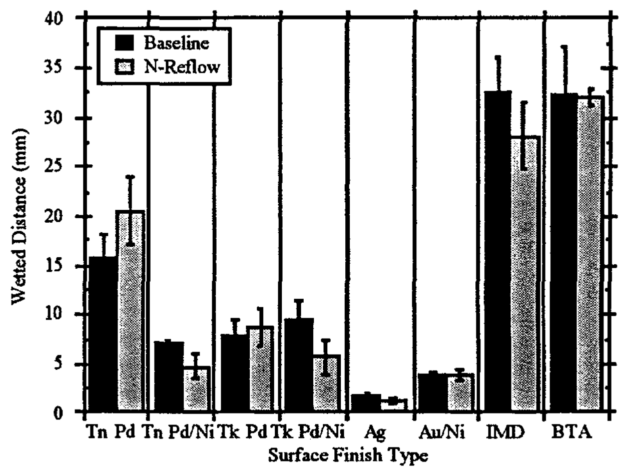

Figure 8: Solder flow comparison of baseline vs. single pass, N_2-reflow aged 30 mil lines, for different surface finishes. Solder tests conducted with RMA flux.

Since the wetting results were relatively poor for the baseline metallic surface finishes tested with R and LS flux, a comparison of the three flux types was not made for all of the aged samples. However, the R flux did yield good solder flow results for both OSP coatings and was included in the aging evaluations. Under these test conditions, the RMA flux yielded consistently better solder flow results than the R fluxed samples. The flow data are summarized in Fig. 9. The bar graph compares the IMD and BIMD finishes in the baseline and environmental stressed conditions.

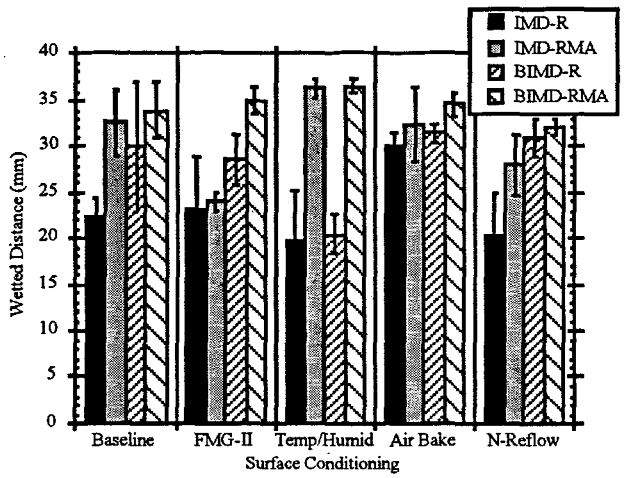

Figure 9: Solder flow comparison for different surface treatments on two OSP-coated Cu finishes. Solder tests conducted on 30 mil lines with RMA or R flux.

The BIMD OSP was least affected by the choice of flux. Wetted distances on these samples ranged from 30 to 35 mm for the R and RMA flux, respectively. The exception was the temperature/humidity stressing condition, where solder flow was only 20 mm with the R flux, compared to almost 37 mm with the RMA flux.

There was clearly more variation in the solder flow results for the IMD finish and the two rosin-based fluxes. This flow difference was approximately 10 mm or greater between the R and RMA flux, a value much higher than that measured on the BIMD finish. This difference was lower on the FMG-Class II aged and air baked IMD samples, with wetting being within 1 mm or less, regardless of rosin type. The absolute results, however, were still lower than those of comparable BIMD treated surfaces.

From these baseline and aging test results, the effectiveness of the different surface finishes can be ranked. The organic coatings clearly provided better protection than the metallic finishes for the investigated conditions. Of the metallic coatings, thin Pd over Cu yielded the best solder flow distances, although the lengths were generally one third to one half of the OSP values with RMA flux. The BIMD coatings gave the best overall flow results, even when compared to the IMD finish. The RMA flux was the most effective one tested, regardless of surface finish. The LS flux produced the poorest baseline flow results and was not included in the subsequent aging evaluations.

CONCLUSIONS

A pad/line test geometry was used to investigate the effects of surface finish and environmental stressing on solder flow. The organic, azole-based coatings provided the most effective and consistent protection during simulated storage and thermal aging of the underlying Cu PWB features. RMA flux also improved solder flow on the aged coupons. Of the metallic coatings, the thin Pd over Cu finish yielded the best solder flow results compared to the thin Pd over Ni/Cu, thick Pd over Cu, thick Pd over Ni/Cu, Ag over Cu, and Au over Ni/Cu finishes. Solder flow was reduced by increasing the intermetallic precipitates in the bulk solder, whose concentration was controlled by the initial thickness of primary metallic finish.

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