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An investigation on the coating of 3003 aluminum alloy

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Abstract

A new approach to reduce the decomposition of electroless Ni-P deposition solution during coating of 3003 aluminum alloy was verified. This new approach uses an immersion coated Cu layer to protect the subsequent electroless deposition solution from being contaminated by the dissolution of substrate. Water rinsing of pretreated 3003 Al substrate prior to immersion coating was, however, found to have an effect on the subsequent immersion coating process, and a new rinsing process with significant beneficial effect was developed. AFM and SEM were used to observe the effect under different conditions. XPS was applied to study the surface changes so as to understand the effect. Successful rinsing yielded satisfactory immersion copper coating which was, in turn, found beneficial to the stability of the subsequent electroless deposition bath.

Key words: rinsing, immersion, electroless, aluminum

1. Introduction

Aluminum is characterized of three main properties on which its application is based: a low density of approximately 2.7 g/cm^3 , the high mechanical strength achieved by suitable alloying and heat treatments, and the relatively high

corrosion resistance of the pure metal. Other valuable properties include high thermal and electrical conductance, reflectivity, high ductility and resultant low working cost, magnetic neutrality, high scrap-value, and the non-poisonous and colorless nature of its corrosion products which facilitates its use in the chemical and food-processing industries. Of particular interest to many industries is its strong electro-negativity and therefore a strong affinity for oxygen which is apparent from the high heat of formation of its oxide. A very thin but tenacious oxide film forms which covers the aluminum surface as soon as a freshly-cut piece of the metal is exposed to the atmosphere. This makes pure aluminum an excellent corrosion resistant material for many applications. However, in its pure state, aluminum is a relatively soft metal with a yield strength of only 34.5 N/mm^2 ($5,000 \text{ lb/in}^2$) and a tensile strength of 90 N/mm^2 ($13,000 \text{ lb/in}^2$). The availability of a wide range of alloys with varied strengths and ductility has led to numerous applications. These applications, for example, range from the use of very thin foil material in the packaging industry, ductile materials for drink containers, and highly conductive alloys for electrical applications, relatively low-strength alloys for the building industry to high strength materials for aircraft and armored vehicles.

Aluminum in its pure state has a relatively high corrosion resistance and needs less protection than most metals. On the other hand, the commercial aluminum alloys, though mechanically more versatile, are distinctly more sensitive to corrosion, and the development of high strength light alloys, containing quantities

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of heavy metals such as copper, zinc or nickel, has heightened the need for protective surface treatments. The nature of the heavy metal additions appreciably influences the alloy's susceptibility to corrosion, and high mechanical strength and corrosion resistance have so far proved largely incompatible. The development of satisfactory protective finishes for these metals has been, therefore, of significant importance ^[1].

Many finishes are applicable to aluminum and its alloys including cathodic systems, metal spray, sealants, inhibitors and protective coatings including chemical conversion coatings, anodic oxidation coatings, organic finishing, vitreous enamel finishes, electroplated finishes and electroless deposition. Research and development on electroless deposition, particularly nickel, continues to increase, as it offers a route to the fabrication of a "composite" of light weight, good thermal conductivity with excellent combined functional properties, such as good corrosion resistance, good abrasion resistance, good solderability, high hardness, and good sliding wear resistance.

Electroless nickel deposition, as a coating technique, possesses a unique combination of the following characteristics as compared to other processes [2, 3]:

- Applicable to substrates of complicated shapes and sizes and generates coatings of uniform thickness. The coatings are superior to those produced by electroplating where the 'throwing power' of the bath may act as a limiting factor.

- No electric current flow through the substrate is required which reduces the complexity for process control.
- Simple and safe operation. Work piece is immersed in a chemical solution to start deposition. No electrical operations and maintenance. No electric discharges during the process.
- No physical and/or mechanical damage to the substrates when properly conducted.
- The process provides excellent protection to aluminum in terms of corrosion and wear. Electroless nickel deposition forms an alloy rather than a pure metal coating. The composition of the alloy varies depending on the bath composition and the operating conditions, thus providing the possibility to optimize the corrosion protection effect in different mediums. In addition, electroless deposited alloy, Ni-P, for example, is generally twice as hard as pure nickel and exhibits excellent wear resistance.

However, there are certainly technical limits to the use of aluminum and its alloys, not least because not all alloys allow the deposition of sufficiently adherent or corrosion resistant electroless nickel deposition. Also, dissolution of aluminum, both in acidic and in alkaline solutions, causes contamination of the bath which leads to the decomposition of the electroless deposition solution, a major challenge in the application of electroless deposition process. The electroless deposition on aluminum therefore calls for a pretreatment sequence

which is significantly different from the conventional types of pretreatment used for steels or copper-based alloys. At the heart of the difficulties in aqueous deposition of metals onto aluminum or its alloys, lies in its very high affinity for oxygen. Aluminum and its alloys are covered in their natural state by a tightly adhering and dense oxide film, about $0.02\mu\text{m}$ thick, which forms on exposure to the atmosphere. Freshly exposed aluminum is rapidly covered with an oxide film in aqueous solution which impedes the formation of a metal-to-metal bond with the deposited metal. Direct electroless deposition on aluminum, therefore, usually exhibits unsatisfactory adhesion [4]. Therefore, the development of a special procedure prior to electroless deposition was necessary. After the unavoidable stages of cleaning, etching or activation, the following two basic methods of pretreatment have been developed: (i) formation of a thin immersion coated layer of zinc, tin, iron, nickel, (ii) treatment of a porous oxide film by chemical or anodic oxidation. Immersion coating process is more often used due to the simplicity and low cost of the process. However, it ought to be mentioned that formation of an immersion layer on aluminum alloys normally happens on an individual case basis due to the vastly available variations of aluminum alloy compositions and post-treatment schemes, which lead to complicated variations of surface chemical sensitivity. Challenges could also exist due to the rapid passivation of aluminum surface, forming an impeding layer during the pretreatment procedures prior to immersion coating. The present communication reports a recent development on coating of 3003 aluminum alloy by means of immersion copper and a subsequent electroless Ni-P deposition.

2. Experimental

The aluminum substrate used throughout the experiments is 3003 aluminum alloy with a nominal composition of Cu (0.05 to 0.2%), Si (0.60%), Fe (0.70%), Mn (1.0 to 1.5%) and Zn (0.10%). Specimens were prepared with dimensions of 30mm×10mm×0.5mm. In order to ensure the accuracy of deposition rate measurement, all the samples were weighed before and after coating using Ohaus Model AP250D Analytical Balance with a resolution of 10^{-4} g. De-ionized water (>15 Mohms.cm⁻¹) used was prepared with Millipore Elix 10 Water Deionization system, filtered to remove hydrocarbons. Chemicals, NaOH, NiSO₄·6H₂O, CuSO₄, HNO₃, H₂SO₄, C₄H₆O₆ of AR grade, used in this work were provided by SIGMA.

3. Results & Discussion

3.1 Alkaline cleaning and acid etch

The efficiency of the preliminary cleaning process is important for almost every type of metal finish and can be paramount in some cases. A clean surface plays a crucial role in achieving a successful subsequent deposition particularly with respect to good coverage and adhesion. In metal finishing, a differentiation is often made between physically and chemically 'clean' surfaces. Physical cleanness in the sense of apparent freedom from solid dirt, grease, or other contamination is, in general, insufficient to ensure either the successful application of a finishing operation or maximum corrosion resistance; Chemical cleanness, refers to the absence of any contamination

in the form of oxides and/or silicon, for example. While alkaline cleaning is to deal with both the physical and chemical cleanliness in this work, the acid etch is to ensure a chemical cleanliness of a physically clean surface particularly when the 3003 aluminum alloy contains both copper and silicon in its composition. The oxide on the aluminum surface is regarded as a chemical contaminant which is detrimental to subsequent coating process.

In order to achieve a good cleaning, an etching based cleaner, aqueous NaOH solution, was used in this work for the cleaning of specimen surface.

The operating temperature was controlled using NESLAB GP200 water bath with a control accuracy of $\pm 1^{\circ}\text{C}$. It should be mentioned that a cleaning solution is normally expected to wet the surface uniformly and immediately in order to produce a uniformly finished surface. Alkalis in general are poor wetting agents and water, with a surface tension of 73 dynes/cm, does not readily wet oils, which have relatively low surface tensions. Even though the samples used are not visually contaminated with oil, the cleaning process was still facilitated with ultrasound to ensure a reliable cleaning. The value of ultrasonic cleaning lies in the mechanical scrubbing action that occurs as the fluid is ruptured and then reformed and this takes place at a rate equal to the frequency of the energy input. The ultrasonic system used in our experiments is the Model FS60 ultrasonic bath from Fisher Scientific. After cleaning in hot alkaline solutions, or after a sodium hydroxide-based etch, a black/gray residue, was left on the aluminum surface. This residue tends to be heavier on aluminum alloys with a higher percentage of alloying elements.

It consists of particles of oxide, intermetallics, silicon, etc., which are insoluble in the alkaline solution, and in general are quite loosely held on the surface. For this reason, a subsequent acid etching is normally required.

Experiments on the NaOH concentration, solution temperature and duration of cleaning were conducted, with the results shown in Tables 1 to 3. The wettability and surface appearance were used as a guide to select the optimum cleaning conditions. While the surface appearance was visually evaluated, the wettability of the surface was evaluated by measuring the surface contact angle, as there exists an intimate link between contact angle and wettability or hydrophilicity ^[5]. The contact angle measurement was conducted for surfaces subjected to different cleaning in order to optimize the operation conditions. The system used was a Cam -Micro contact angle meter manufactured by Kernco Instruments Inc equipped with a microsyringe attachment. Deionized water of greater than 15 Mohms.cm⁻¹ was employed as the probe liquid. Four measurements were made on each sample, and the data are presented as a range in Tables 1 to 3. Based on the results, an operating condition of 7g/L NaOH, 50 °C and 150 seconds was determined to be optimum by a combined assessment of hydrophilicity and appearance of the cleaned surface. The samples cleaned under these conditions were then subjected to acid etch in 30 % HCl at 25 °C for 30 seconds for residue removal, with a resulting contact angle of 10° ~ 14° and a silver gray color.

3.2 Water rinsing – a challenge encountered

What appeared to be a routine water rinsing prior to immersion copper coating was found to affect the subsequent coating process significantly: rinsing for more than 3 seconds in water prevented the formation of immersion coating, and a less than 3 second rinse led to very inconsistent deposition in view of the surface coverage. This posed a significant engineering challenge for process control and product consistency due to the tight operation window. The problem was not solved until a small amount of additive, HCl, was added. This additive was found to be highly effective from extensive research at IMTI of the National Research Council Canada. This discovery significantly broadened the operation window of rinsing from less than 3 seconds to exceeding 60 seconds. The effect of additive concentration on the deposition rate is shown in Figure 1. As can be seen that 1 ml of additive per liter of water yields the highest deposition rate for subsequent immersion copper coating. It is of note that a concentration lower than 1 ml/L leads to skips and voids in the deposit and poor adhesion while too high a concentration leads to corrosion of the substrate.

3.3. AFM, SEM and EDX analysis

In order to demonstrate the effect of different rinsing conditions on the subsequent immersion copper coating, atomic force microscope (AFM) analysis was employed, using Topometrix Explorer AFM system, to compare the morphologies of the substrates subjected to the same cleaning and etching but rinsed in water, with and without additive, followed by identical

immersion Cu coating process. The images were obtained using dynamic force (or tapping) mode with a stiff cantilever (125 μm long, 35 μm wide and 4 μm thick). The spring constant is ~ 40 N/m and the radius of the tip apex is ~ 20 nm. Images of an area of 50 $\mu\text{m} \times 50 \mu\text{m}$ were obtained. The scan rate was 50 $\mu\text{m/s}$. There are 500 points of data in one line and 500 lines in an image.

Figures 2 and 3 depict the 3D expressions of immersion coated 3003 Al alloy substrates rinsed in water with and without additive for 3 seconds, respectively. Their corresponding 2D images are shown in Figures 4 and 5, respectively. Both samples were subjected to the following treatments:

Alkaline cleaning: 7 g/L NaOH, 50 $^{\circ}\text{C}$ for 150 seconds

Acid etch: 30 % HCl at 25 $^{\circ}\text{C}$ for 30 seconds

Water rinse (with and without additive)

Immersion copper coating: $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (30 g/L), $\text{C}_4\text{H}_6\text{O}_6$ (tartaric acid) (53 g/L) at 25 $^{\circ}\text{C}$ for 3 minutes

It can be seen that the sample rinsed with water was only covered on certain spots after 3 minutes immersion coating, Figures 3 & 5, while the one rinsed with additive containing water resulted in a significantly improved surface coverage, Figures 2 & 4. The grain size on the samples ranges from 0.7 μm to 1.5 μm .

In order to verify the grains observed under AFM are copper, SEM/EDX analysis was conducted using the TMPersonalSEM manufactured by R J Lee Instruments.

Shown in Figure 6 is the SEM image of the immersion coating on the

substrate rinsed with water without additive. Figures 7 & 8 are the EDX spectra corresponding to spots labeled in Figure 6. It is clearly shown that the surface is only partially coated with Cu, Figure 6 - spot 1 & Figure 7 even though there exist copper deposits, Figure 6 – spot 2 and Figure 8.

On the contrary, copper immersion coating on the substrate rinsed in water with additive demonstrates a much higher coverage on the surface, shown in Figures 9 to 12. The EDX results at different areas of the coated surface shows a consistent Cu coverage ranges from 99.38% to 99.83%. The very low level of Al detected might be because of the penetration of electron beam through the thin immersion coated copper layer.

3.4 XPS analysis

In order to understand the cause of inhibition of deposition on the aluminum surface rinsed with water, X-ray Photoelectron Spectroscopy (XPS), Model SSX-100 ESCA Spectrometer, was employed to analyze the aluminum surface rinsed in water and in the water with additive. Survey analyses were carried out using a 600 μm spot size and a pass energy of 150 eV. Detection limits are ranged around 0.01 to 0.1 atomic percent. High resolution analyses were carried out using a 600 μm spot size and a pass energy of 50 eV.

Full surveys of the substrate surfaces rinsed in water with and without additive are shown in Figures 13 to 14, respectively. In order to verify the reliability of the results, high resolution scans on carbon peaks were

conducted with the results shown in Figures 15 and 16. The binding energy of carbon in both cases, 284.91 eV in Figure 15 and 284.95 eV in Figure 16, is consistent with the standard binding energy of carbon which is about 294.9 eV. This demonstrates a reliable scan without significant charging on the surface. In addition, the binding energy value reveals that the carbon observed on the surface is adventitious carbon originated from sample transfer in air.

High resolution scans were then carried out for both samples rinsed in water with and without additive, shown in Figures 17 and 18, respectively. The results showed that there exists a double peak in both cases corresponding to Al and Al_2O_3 at a binding energy of 72.76 eV and 74.81 eV for the surface rinsed in water with additive, and at 72.67 eV and 74.68 eV for the surface rinsed in water without additive, shown in Tables 4 and 5, respectively. It ought to be mentioned that the existence of Al_2O_3 , even on the sample rinsed in additive containing water, is understandable as aluminum is easily oxidized in air particularly when the water film formed during rinsing is removed. Even though the samples after rinsing were dried and sealed in a polyethylene bag immediately, oxidation of the surfaces cannot be avoided due to the strong chemical affinity of aluminum to oxygen. The lower oxide coverage on the surface rinsed in water with additive is indicative of an inhibition effect of the additive on the oxidation of aluminum which resulted in a higher exposure of Al to the subsequent copper immersion solution. In addition, more detailed analysis of the oxide film thickness on the surface can be done using the

model established by Strohmeier ^[5].

$$d(\mu\text{m}) = 2.8 \ln(1.4I_o / I_m + 1)$$

where d is the oxide thickness, I_o and I_m are the normalized oxide and metal photoelectron peak areas, respectively. Using the peak area data in tables 4 & 5, the oxide thickness values for the surfaces rinsed in water with and without additive are 5.74 μm and 6.69 μm , respectively, which further confirmed the inhibition effect of the additive on the oxide formation.

It should be mentioned that rinsed samples are transferred immediately into the immersion Cu coating bath without drying. The water film on the surface prevents a direct contact between Al surface and air thereby reduces oxidation. However, that fact that samples rinsed for less than three seconds in water without additive can be easily coated suggests that the substrate surface can be oxidized, even in water, to an extent that immersion Cu deposition is prevented. The inhibition effect of the additive, however, opens a much wider window for the surface to be exposed to water without significant oxidation, evidenced by the full Cu coverage even after 60 seconds rinse. It is therefore easily understandable that a much higher Cu coverage, evidenced by the AFM and SEM analysis (Figures 2-6 & 9), can be achieved because Al, but not Al_2O_3 , acts as the reducing agent during immersion coating process following the reaction shown below.

3.5 Electroless nickel deposition

Electroless deposition was carried out on immersion Cu coated 3003 aluminum alloys surface. The deposition bath composition and operating conditions are given below.

30 g/L $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$

20 g/L CH_3COONa

20 g/L $\text{NaH}_2\text{PO}_2 \cdot x\text{H}_2\text{O}$

pH = 4.5, Temperature = 70 °C

Deposition time: 120 mins

Shown in Figure 19 is the SEM morphology image of electroless Ni-P deposit. Figure 20 is the corresponding EDX elemental analysis which shows the Ni and P composition. As seen in Figure 19, a uniform Ni-P was achieved on the immersion Cu coated aluminum substrates. No decomposition of the bath was observed even after 15 hours of continuous deposition. This is a significant improvement of bath stability as compared to the direct electroless deposition on the aluminum substrate in which case the bath decomposes in 30 minutes and the surface was severely corroded.

Vicker's hardness of the uncoated and electroless nickel coated 3003 aluminum alloy was conducted using the Model Buehler Micromet II Micro Hardness Tester. Ten points were measured on each sample. The results showed a significant increase of surface micro hardness from 47 Hv on the uncoated aluminum alloy to 760Hv on the Ni-P coated surface.

Wear testing was also conducted using pin-on-disk test method (ASTM G99-95a). For the pin-on-disk wear test, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk center. In either case, the sliding path is a circle on the disk surface. Material volume loss in the circular track after a certain number of rotations is recorded to evaluate the wear resistance [6]. In this research, Falex ISC Pin-On-Disk Tribometer (Model 200PC) interfaced with Falex PC-Stripchart was used. Tungsten carbide (94%WC + 6% Co) ball of 1/8" in diameter was used as the pin. The wear track radius was 4.5 mm and the rotation rate was 100 rpm. The load applied on pin was 50 g. The wear test results for uncoated and electroless Ni-P coated 3003 Al alloy are given in Table 6. The results show that the volume loss of uncoated sample was 0.44 mm³ after only 3000 rotations while the Ni-P coated sample has only 0.0016mm³ volume loss even after 20000 rotations. The calculations were carried out using the equation shown below:

$$disk\ volume\ loss = 2\pi R[r^2 \sin^{-1}(d / 2r) - (d / 4)(4r^2 - d^2)^{1/2}]$$

where:

R is the wear track radius, d is the wear track width and r is the pin end radius.

It ought to be mentioned that the volume loss of coated sample after 3000

rotations was not measurable and hence a 20000-rotation test was conducted. On the other hand, however, aluminum particles worn off the sample was found to stick to the surface of the pin when conducting a more than 3000-rotation test on the uncoated aluminum surface which would lead to an inaccurate measurement.

In summary, addition of additive in the rinse water has a significant effect on opening the operation window, from 3 seconds to 60 seconds, and improving the coating consistency. The uniform immersion copper coating formed on 3003 Al alloy render a successful subsequent electroless nickel deposition with a much higher bath stability. The hardness of the surface is increased from 47Hv to 760 Hv while the wear resistance of the surface was also significantly increased.

4. Conclusions

- Water rinse was found to inhibit subsequent immersion deposition of Cu possibly due to the formation of oxide on the surface
- An acidic additive was found to be effective in inhibiting the formation of oxide on the surface which render a much wider window of rinse for subsequent immersion deposition of Cu with consistency and ease of operation.
- The immersion coated Cu layer prevented Al from direct contact with the subsequent electroless nickel deposition solution thereby increased the stability of the electroless deposition bath.
- The electroless Ni-P coated 3003 Al alloy was rendered a much higher

hardness and wear resistance.

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Table 1. Temperature effect on the degreasing effect

Temperature (°C)	20	40	50	60	80
Observation of substrate surface	Bright silver	Silver	Gray	Dark gray	Black
Contact angle (°) (after degreasing)	70 ~ 74	60 ~ 70	52 ~ 64	24 ~ 32	12 ~ 18

Table 2 NaOH concentration effect on the degreasing effect

Concentration (g/L)	2	5	7	10	15
Observation of substrate surface	Bright silver	Silver	Gray	Dark gray	Black
Contact angle (°) (after degreasing)	22 ~ 30	14 ~ 28	< 10	< 10	< 10

Table 3 Effect of duration of alkaline cleaning on the degreasing

Duration (seconds)	60	90	120	150
Observation of substrate surface	Bright silver	Silver	Grayish silver	Light gray
Contact angle (°) (after degreasing)	52 ~ 62	48 ~ 52	30 ~ 48	25 ~ 30

Table 4. High resolution ESCA analysis results of 3003 Al alloy rinsed in water with additive (baseline start: 78.23 eV, baseline end: 70.67 eV, normalized baseline area: 614.384)

Peak Label	Binding Energy (eV)	FWHM	Peak Height	Normalized area	Area percentage	G/L ratio
A (Al metal)	72.76	0.97	802.59	108.32	17.1%	90.0%
B (Al ₂ O ₃)	74.81	1.89	1986.68	523.394	82.9	90.0

Table 5. High resolution ESCA analysis results of 3003 Al alloy rinsed in water without additive (baseline start: 78.07 eV, baseline end: 70.67 eV, normalized baseline area: 582.45)

Peak Label	Binding Energy (eV)	FWHM	Peak Height	Normalized area	Area percentage	G/L ratio
A (Al metal)	72.67	0.96	440.353	73.4086	12.4%	90.0%
B (Al ₂ O ₃)	74.68	1.97	1511.61	518.57	87.6	90.0%

Table 6 pin-on-disk wear test results of coated and uncoated 3003 Al alloy samples

Specimen	No. of rotation	Volume loss (mm ³)	Width of the wear track (μm)	Depth of the wear track (μm)
Uncoated	3000	0.44	840	57.4
Ni-P coated	20000	0.0016	129	3

Figure 1. Deposition rate of immersion Cu coating vs. duration of rinsing in additive containing water

Figure 2. AFM image of immersion copper coated 3003 Al alloy rinsed in water with additive

Figure 3. AFM image of immersion copper coated 3003 Al alloy rinsed in water without additive

Figure 4. 2D expression of the AFM image of immersion copper coated 3003 Al alloy rinsed in water with additive

Figure 5. 2D expression of the AFM image of immersion copper coated 3003 Al alloy rinsed in water without additive

Figure 6. SEM image of immersion copper coated 3003 Al alloy rinsed in water without additive (2500X)

Figure 7. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water without additive, showing voids of deposit

Figure 8. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water without additive, showing areas of Cu deposit

Figure 9. SEM image of immersion copper coated 3003 Al alloy rinsed in water with additive, showing full Cu coverage (2500X)

Figure 10. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water with additive, showing Cu coverage even in lower site

Figure 11. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water with additive, showing Cu on high site

Figure 12 EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water with additive, showing Cu deposit on a different high site

Figure 13 XPS survey of etched 3003 Al alloy rinsed in water with additive

Figure 14. XPS survey of etched 3003 Al alloy rinsed in water without additive

Figure 15. High resolution XPS scan of carbon peak on etched 3003 Al alloy rinsed in water with additive

Figure 16. High resolution XPS scan of carbon peak on etched 3003 Al alloy rinsed in water without additive

Figure 17. High resolution XPS scan of aluminum/oxide peaks on etched 3003 Al alloy rinsed in water with additive

Figure 18. High resolution XPS scan of aluminum/oxide peaks on etched 3003 Al alloy rinsed in water without additive

Figure 19. Morphology of electroless Ni-P deposit on immersion Cu coated 3003 Al alloy (2000X)

Figure 20. EDX compositional spectrum of electroless Ni-P deposit

Captions

Figure 1. Deposition rate of immersion Cu coating vs. duration of rinsing in additive containing water

Figure 2. AFM image of immersion copper coated 3003 Al alloy rinsed in water with additive

Figure 3. AFM image of immersion copper coated 3003 Al alloy rinsed in water without additive

Figure 4. 2D expression of the AFM image of immersion copper coated 3003 Al alloy rinsed in water with additive

Figure 5. 2D expression of the AFM image of immersion copper coated 3003 Al alloy rinsed in water without additive

Figure 6. SEM image of immersion copper coated 3003 Al alloy rinsed in water without additive (2500X)

Figure 7. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water without additive, showing voids of deposit

Figure 8. EDX spectrum of immersion copper coated 3003 Al alloy rinsed in water without additive, showing areas of Cu deposit

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