"The Properties and Structure of Electroless Nickel-Boron Coatings"

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ABSTRACT

The properties of deposits from baths reduced with dimethylamine borane or sodium borohydride are similar to those of electroless nickel-phosphorus alloys with a few exceptions. The hardness of nickel-boron alloys is very high and they can be heat treated to levels greater than that of hard chromium. Nickel-boron coatings thus have outstanding resistance to wear and abrasion. These coatings, however, are not as strong or ductile as electroless nickel-phosphorus. In addition, they are not amorphous and have reduced resistance to corrosion.

This paper describes the properties of electroless nickel coatings reduced with boron compounds and how they vary with changes in deposit composition. The effect of composition on the metallurgical structure of the coating is also described and compared with that of nickel-phosphorus alloys.

Different electroless nickel plating solutions are designed with different chemicals and for different objectives. In addition to the more common nickel-phosphorus alloys, two types of electroless nickel-boron coatings are commercially available. These two types of coatings vary both by the reducing agent used and by the composition of their deposits.

DMAB Baths. Plating baths reduced with dimethyl amineborane were one of the earlier developments in the electroless nickel industry. These solutions are typically complexed with glycolic acid or glycine with acetate buffers. They can produce coatings containing 2 or 3 percent boron, but are normally formulated and operated to provide deposits containing less than ½ percent boron.

The low boron coatings offer superior conductivity, solderability and bonding, when compared with other electroless nickel deposits. Accordingly, they are most commonly used for electronic applications, especially on nonmetal substrates. However, because of their high cost, the market for DMAB reduced coatings is small, equaling only about ½ percent of the total coatings applied in North America.

DMAB reduced baths are normally operated at 50DegC, although some formulations can be operated at temperatures as low as 30DegC. The optimum pH varies with the bath formulation and can be between 6.8 and 7.3. The plating rate of these solutions is the lowest of commercial baths, and is typically 7 to 9 μm/h. DMAB reduced baths are operated in much the same way as hypophosphite reduced solutions, requiring only periodic analyses for nickel and pH and occasional analysis of the reducer. DMAB reduced plating baths are only available from a few suppliers. A typical composition and operating conditions for an amineborane bath are listed in Table 1.[1]

Borohydride Baths. Borohydride reduced coatings were developed in the 1960's in Europe and the USA independently by BASF and DuPont. They were more commonly used in Europe, where they were trade named Nibodur. Until recently, they were only available from one plating house in the USA, whose trade name for them was Nibron. In the 1990's, a revival of interest in this coating occurred, especially in the aerospace and automotive industries, and several new facilities have opened.

To prevent hydrolysis of the borohydride, these baths must be operated at 12 to 14 pH. They are complexed with ethylene diamine to prevent precipitation of nickel hydroxide. Both Nibodur and Nibron are stabilized with thallium, which also codeposits with the coating. Nibodur coatings typically contain 5 percent boron and 4½ percent thallium, Nibron contains 3½ percent boron and 3½ percent thallium. The principal advantage of these coatings is their very hardness and outstanding resistance to abrasion and wear. After heat treatment, are superior to hard chromium in many applications.

Table 1
Typical Borane and Borohydride Reduced Solutions

Component	**DMAB Reduced**	**Borohydride Reduced**
$NiSO_4$, g/L	27	
$NiCl_2$, g/L		20
DMAB, g/L	2.5	
Sodium borohydride, g/L		0.4
Glycolic acid, g/L	30	
Acetic acid, g/L	15	
Sodium hydroxide, g/L		90
Ethylene diamine, g/L		90
Thallium sulfate, g/L		0.04
pH	6 - 7	14
Temperature, DegC	60	95
Boron content, %	0.4	5
Plating rate, □m/h	7 - 10	20 - 25

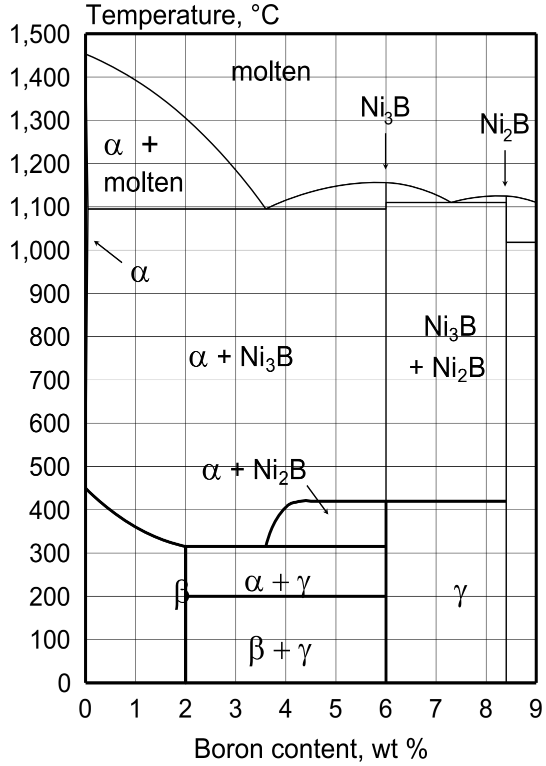
Borohydride reduced baths are typically operated at 90 to 95 DegC. The baths are used without aeration and usually with mechanical agitation. The plating rate of most baths is about normally 15 to 20 μ/h. However, because of their high pH, these baths cannot be used to plate aluminum substrates directly. Aluminum parts must first be coated with an acid hypophosphite reduced bath.

With borohydride reduced baths, the ratios of nickel, borohydride, alkalinity, ethylene diamine and thallium are critical and should be carefully monitored and adjusted. Bath chemicals are best added continuously in small amounts during operation, rather than by batch replenishment. Either automatic or frequent manual analysis of the solution's components are often required to keep the bath in balance and to ensure optimum deposit properties. The composition and operating conditions of a borohydride reduced electroless nickel bath is also shown in Table 1.[2]

The properties of electroless nickel-boron coatings are similar to those of nickel-phosphorus coatings with a few exceptions. The properties of these coatings are compared with typical nickel-phosphorus coatings in Appendix 1 and are described in the following paragraphs.

Structure. While the structure of nickel-boron deposits has not been studied as completely as that of the nickel-phosphorus coatings, it does appear to have similar phases and transitions. The different phases that are present in nickel-boron coatings are shown in the phase diagram in Figure 1.[3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14]

Figure 1
Phase Diagram for Ni-B Coatings



Those coatings containing less than about 2 percent boron consist of a microcrystalline, solid solution of boron in nickel, like the beta phase in nickel-phosphorus alloys. Coatings containing more than about 6 percent boron are amorphous. The structure of coatings containing between 2 and 6 percent boron, is a mixture of microcrystalline and amorphous phases.

On a cross section, borohydride reduced coatings have a columnar structure that is the result of the hemispherical nucleation and growth of the deposit. A cross sectional view of a coating containing 3½ percent boron and 3½ percent thallium is shown in Figure 2. On the surface this columnar growth produces an orange peel appearance with nodules separated by cracks and ditches. This surface condition can often be useful in retaining lubricants under conditions of adhesive wear.

Also like the nickel-phosphorus coatings, nickel-boron deposits harden by a series of decomposition reactions when they are heated. With coatings containing less than about 6 percent boron, alpha nickel begins to precipitate at temperatures above 200DegC, beginning the hardening process. Then at 300DegC, nickel boride (Ni_3B) forms further hardening the coating. Finally, with coatings containing more than about 4 percent boron, Ni_2B precipitates at about 400DegC. These reactions can produce hardness values much higher than those of the nickel-phosphorus alloys and higher even than hard chromium.

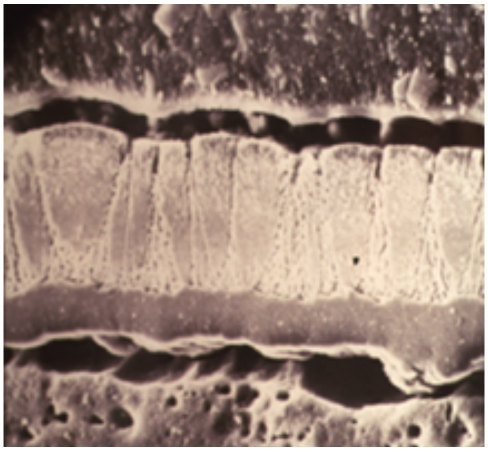
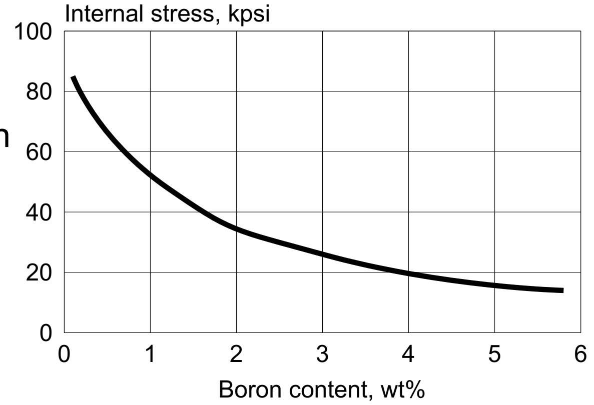


Figure 2
Cross Section of Ni-B-TI Coating

Appearance. The appearance of low boron, DMAB reduced coatings is similar to that of nickel and electroless nickel-phosphorus coatings. Borohydride reduced, nickel-boron-thallium deposits, however, are matt in appearance and light charcoal grey in color.

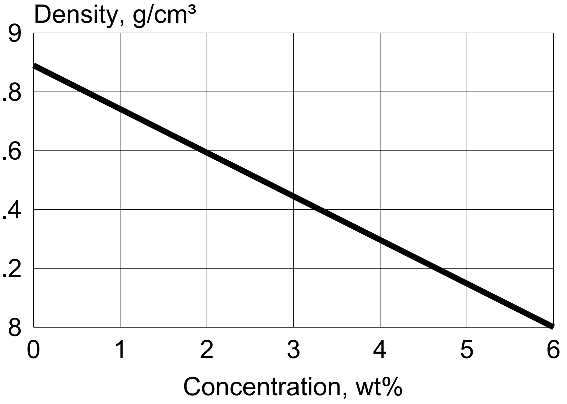
Internal Stress. Stress of nickel-boron deposits varies with boron content. Unlike the nickel-phosphorus alloys, however, the internal stress of nickel-boron coatings is always highly tensile. Neither low nor high boron coatings are compressive. As shown in Figure 3, the internal stress of these coatings varies from almost 500 MPa for a DMAB reduced coating containing 0.4 percent boron to 110 MPa for a borohydride reduced deposit containing 5 percent each of boron and thallium.[15] [16]

Figure 3
Effect of Boron Content On Internal Stress



Physical Properties. The physical properties of nickel-boron coatings also vary with their boron content. The initial melting point for these alloys is 1080DegC, which is 200DegC higher than that of the nickel-phosphorus coatings. As shown by the phase diagram in Figure 1, the final melting point varies from 1080DegC at the eutectic point at 4 percent boron to 1450DegC for pure nickel.

Figure 4
Effect of Boron Content On Density

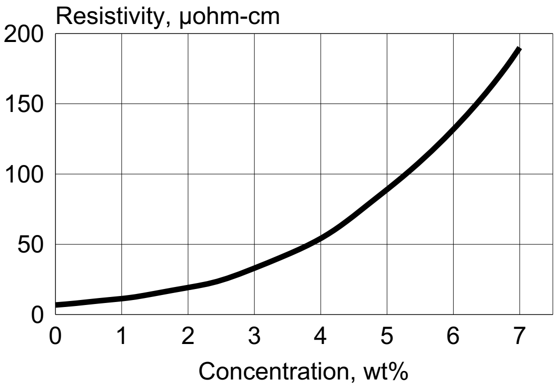


The density of nickel-boron deposits is similar to that of nickel-phosphorus coatings of an equal alloy content. The density of a borohydride reduced coating containing about 5 percent boron is 8.25 g/cm^3 in both the as deposited and heat treated condition.[14] The effect of increasing boron content on the density of different coatings is shown in Figure 4.[14] [17] [18]

No information is available on the thermal expansion of low boron deposits. The coefficient of thermal expansion of borohydride reduced coatings containing 5 percent boron and thallium is 12.1 □m/m/DegC, which is similar to that of high phosphorus coatings and steel. After heat treatment at 350DegC for 2 hours, the coefficient drops to 10.8 □m/m/DegC.[14]

The electrical resistivity of low boron, DMAB reduced coatings is 5 to 13 μ ohm-cm, which is similar to that of pure nickel or electroplated nickel. The electrical resistivity of high boron, borohydride reduced coatings, however, is more like that of nickel-phosphorus deposits, ranging from 89 μ ohm-cm in the as deposited condition to 43 μ ohm-cm after heat treatment at 1100DegC.[14] The effect of boron content on the resistivity of nickel-boron coatings is shown in Figure 5.[14, 17, 19, 20]

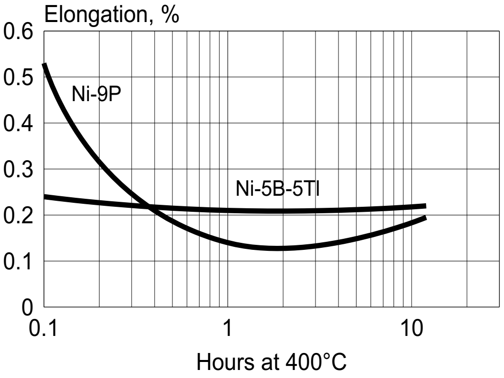
Figure 5
Effect of Boron Content On Electrical Resistivity



The magnetic properties of low boron coatings are like those of pure nickel. In the as deposited condition, borohydride reduced coatings are very weakly ferromagnetic, with coercivities about 10 percent that of pure nickel. Their magnetic susceptibility, however, can be increased significantly by heat treatment at temperatures above 350DegC.[4, 14]

Mechanical Properties. Little is known about the mechanical properties of low boron alloys. The strength and ductility of borohydride reduced coatings containing 5 percent boron and thallium, is only about one-fifth that of high phosphorus coatings. The tensile strength of commercial coatings is about 110 MPa.[16] The modulus of elasticity ranges from 120 GPa in the as deposited condition to 180 GPa after heat treatment at 400DegC for 1 hour.[14]

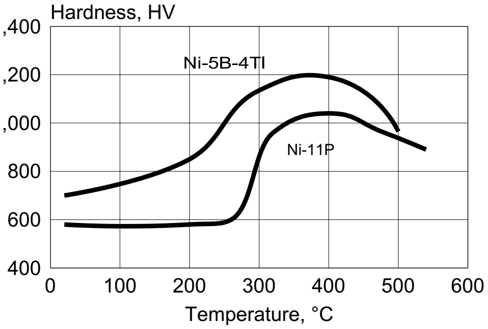
Figure 6
Effect of Heat Treatment On Ductility



The maximum elongation of borohydride reduced coatings is about 0.2 percent.[16] Unlike hypophosphite reduced coatings, however, heat treatment appears to have little upon the ductility of these coatings. Even after 12 hours at 400DegC, bend tests have shown that its strain at fracture declines by only 15 percent.[2] This is illustrated by Figure 6 that compares the effect of heat treatment on the elongation of hypophosphite and borohydride reduced coatings.

Hardness. For many applications, the primary advantage of nickel-boron coatings is their hard hardness and superior wear resistance. In the as deposited condition, the microhardness of coatings containing 4 or 5 percent each of boron and thallium is typically 750 HV$_{100}$. After heat treatment for 1 hour at 350DegC, hardness values of 1200 HV$_{100}$ can be produced. This is much better than most hypophosphite reduced coatings as illustrated by Figure 7.[14][21]

Figure 7
Hardness Of Ni-5B-4Tl and Ni-11P



The concentration of boron and thallium in the coating has a strong influence on its hardness. Figures 8 and 9 show the effects of boron and thallium content in both the as deposited and heat treated conditions.[8][14][15][22][23][24] In the as-deposited condition, maximum hardness occurs at about 2 percent boron, which is the concentration at which a mixture of amorphous and crystalline phases first appears. Also, as-deposited, the addition of 4 percent thallium can increase the hardness of high boron coatings by almost 100 HV units. After heat treatment, hardness increases continuously with boron content and is not effected by thallium additions.

Figure 8
Effect of Boron Content On Hardness

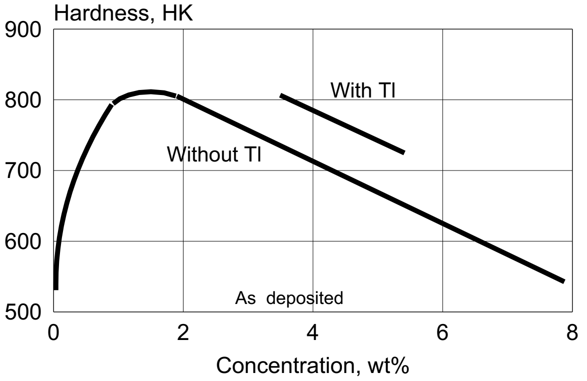
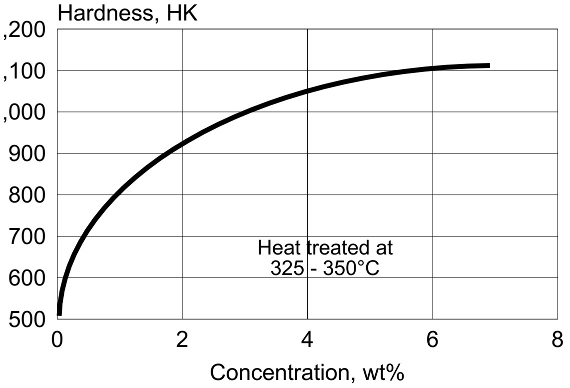


Figure 9
Effect of Boron Content On Hardness



An interesting phenomenon occurs with very long term heat treatments of borohydride reduced coatings on steel substrates. Treatments at 250DegC for 30 to 40 weeks can produce hardness values of 1700 to 2000 VHN$_{100}$.[4][14] This lower temperature treatment apparently causes a finer dispersion of nickel boride and allows the formation of iron borides such as Fe$_2$B and Fe$_3$C$_{0.2}$B$_{0.8}$ from substrate diffusion into the coating.

Heat treatment not only increases the hardness of electroless nickel coatings, but also reduces their ductility. This is true for both nickel-phosphorus and nickel-boron alloys, as shown in Figure 10.[25]

Figure 10

Relationship of Hardness and Ductility

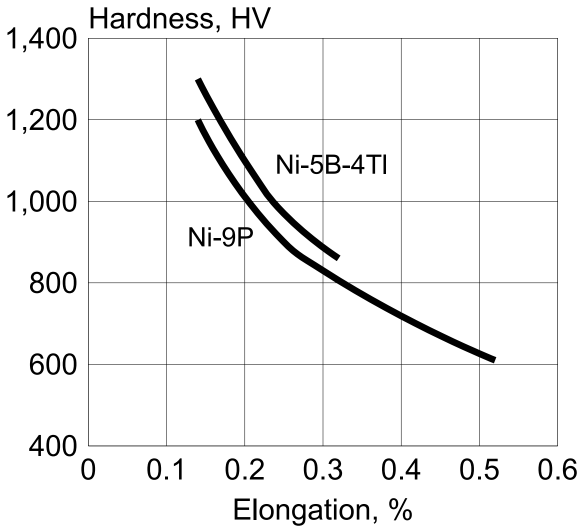


Table 2: Taber Abraser Resistance of Different Coatings

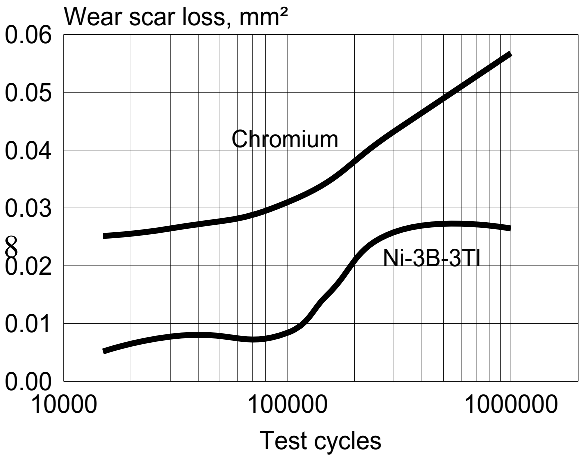
Coating	Heat Treatment	Taber Wear Index
Watts nickel	None	25
Ni-11P	None	19
Ni-11P	400°C/1 hr	10
Ni-5B-5TI	None	9
Ni-5B-5TI	400°C/1 hr	3
Hard Chromium	None	3

Wear Resistance. The wear resistance of borohydride reduced coatings is outstanding and can exceed that of most coatings. Table 2 compares typical Taber Abraser wear test results for a commercial borohydride reduced coating with those for other industrial coatings.[14 21 26 27] Under abrasive wear conditions, high boron coatings offer a significant improvement over either electrolytic or hypophosphite reduced nickel coatings. Hardened coatings are even equal to hard chromium.

Under lubricated conditions, high boron coatings can provide even better wear resistance. Figure 11 compares a borohydride reduced coating with hard chromium under an Alpha LFW-1 adhesive wear test.[28] Even for very long

Figure 11

LFW-1 Wear Resistance of Ni-3B-3TI



test cycles, the wear lost the nickel-boron coating was approximately one half of that of the chromium coating. Falex wear tests with 0.2 and 2 percent boron coatings without thallium, showed them to be generally inferior to higher boron coatings and to hardened nickel-phosphorus coatings against adhesive type wear.[23]

Borohydride reduced coatings are naturally lubricous. Their coefficient of friction verses steel is typically 0.12 to 0.13 when lubricated and 0.43 to 0.44 when unlubricated.[4] [14]

Corrosion Resistance. Usually, the corrosion resistance of nickel-boron coatings is much less than that of coatings reduced with sodium hypophosphite. In environments, such as solvents and alkalies, which cause little corrosion of high phosphorus coatings, nickel-boron is also resistant. However, in environments, such as reducing acids, that cause moderate attack of high phosphorus coatings, nickel-boron can be severely corroded. In strongly oxidizing media neither coating is satisfactory. Appendix 2 summarizes many corrosion tests with Nibodur coatings in many different environments, and shows comparative results with a high phosphorus, electroless nickel-phosphorus.[29]

Table 3: Kesternich Type Corrosion Resistance of Different Coatings

Coating	Cycles to Failure
Ni-11P	10
Ni-9P	2
Ni-5B-4Tl	1
Hard Chromium	1

The difference in corrosion resistance between nickel-boron and nickel-phosphorus coatings is due to the differences in their structure. Low boron coatings are crystalline. High boron deposits are only partially amorphous. Both are typically porous. Because of these factors, the passivation films that form are not as glassy or protective as those which form on high phosphorus coatings. Also, because boron and thallium are not uniformly distributed throughout the coating, areas of different corrosion potential are produced leading to the formation of minute active/passive corrosion cells and accelerated attack.

The different in corrosion protection of phosphorus and boron coatings is dramatically illustrated by the test results shown in Table 3.[30] These tests in a moist SO_2 environment at 40DegC,[31] show that nickel-boron-thallium coatings are no better than chrome in resisting acidic environments.

Conclusion. Electroless nickel-boron coatings have high hardness values, excellent wear and abrasion resistance and good lubricity. Although not as corrosion resistant as the nickel-phosphorus alloys, they can be very useful in improving reliability, extending equipment life and reducing cost in many applications.

Appendix 1

Properties of Electroless Nickel Coatings

Property	**Ni-3P**	**Ni-8P**	**Ni-11P**	**Ni-1/2B**	**Ni-5B-5Tl**
Composition	3 to 4% P, balance Ni	6 to 9% P, balance Ni	11 to 12% P, balance Ni	0.5 to 1% B, balance Ni	3 to 5% B, 3 to 5% Tl, balance Ni
Structure	Micro-crystalline	Mixed crystalline and amorphous	Amorphous	Crystalline	Mixed crystalline and amorphous
Internal Stress	-10 MPa	+40 MPa	-20 MPa	+500 MPa	+110 MPa
Final Melting Point	1275°C	1000°C	880°C	1440°C	1170°C
Density	8.6 g/cm^3	8.1 g/cm^3	7.8 g/cm^3	8.6 g/cm^3	8.25 g/cm^3
Coefficient of Thermal Expansion	12.4 μ /m°C	13 μ /m°C	12.0 μ /m°C	ND	12.1 μ /m°C
Electrical Resistivity	30 μ ohm-cm	75 μ ohm-cm	100 μ ohm-cm	10 μ ohm-cm	89 μ ohm-cm
Thermal Conductivity	0.6 W/cm-K	0.05 W/cm-K	0.08 W/cm-K	ND	ND
Specific Heat	1,000 J/kg-K	ND	460 J/kg-K	ND	ND
Magnetic Coercivity	10,000 A/m	110 A/m	0	ND	ND
Tensile Strength	300 MPa	900 MPa	800 MPa	ND	110 MPa
Ductility	0.7%	0.7%	1.5%	ND	0.2 %
Modulus of Elasticity	130 GPa	100-120 GPa	170 GPa	ND	120 GPa
Hardness, as deposited	700 HV_{100}	600 HV_{100}	530 HV_{100}	580 HV_{100}	700 HV_{100}
Hardness, heat treated	960 HV_{100}	1000 HV_{100}	1050 HV_{100}	500 HV_{100}	1200 HV_{100}
Coefficient of Friction	ND	0.38	0.45	ND	0.44
Taber Wear Index, as deposited	11 mg/1000 cycles	16 mg/1000 cycles	19 mg/1000 cycles	8 mg/1000 cycles	9 mg/1000 cycles
Taber Wear Index, heat treated	9 mg/1000 cycles	12 mg/1000 cycles	12 mg/1000 cycles	8 mg/1000 cycles	3 mg/1000 cycles
Corrosion Protection, salt fog resistance	24 hours	96 hours	1,000 hours	ND	24 hours

ND = not determined

Appendix 2
Corrosion of Electroless Nickel Coatings

Test Solution	Chemical Formula	Temperature, °C	Corrosion Rate, μm/y	
			Ni-5B-5Tl	Ni-11P
Abietic acid methyl ester	$C_{21}H_{32}O_2$	20	0.1	
Acetic acid, 10%	CH_3COOH	20	36	24
99.8%		20	84	0.8
Acetone	$CH_3CO \cdot CH_3$	20	nil	nil
Acetyl acetone	$CH_3CO \cdot H_2\ COCH_3$	20	9.0	
Acetyl chloride	CH_3COCl	20	0.5	
		40	0.4	
		BP	2.0	
Air, 65% relative humidity	–	20	nil	
Aluminum sulfate, 900 g/L	$Al_2(SO_4)_3 \cdot 18H_20$	20	7.0	
Ammonium				
bisulfite, 15%	NH_4HSO_3	20	severe	
chloride, 5%	NH_4Cl	20	24	15
hydroxide, 25% NH_3	NH_4OH	20	40	8
nitrate, 20%	NH_4NO_3	20	severe	
		BP	severe	
phosphate, 5%	$NH_4H_2PO_3$	20	18	
		BP	270	
sulfate, 800 g/L	$(NH_4)_2SO_4$	20	3.5	
Aniline	$C_6H_5NH_2$	20	0.5	
Barium chloride, 5%	$BaCl_2$	20	12	
Benzaldehyde	C_6H_5CHO	20	2.6	
Benzene, sulfur free	C_6H_6	20	nil	
Benzenesulfonic chloride	$C_6H_5SO_3Cl$	20	2.1	
		60	1.5	
Butyl acetate	$C_4H_9OOCCH_3$	20	nil	
–Butyl bromide	C_4H_9Br	20	0.4	
Calcium nitrate, saturated	$Ca(NO_3)_2$	20	1.4	0.2
		118	3.7	
Carbon disulfide	CS_2	20	0.1	
Carbon tetrachloride	CCl_4	20	nil	
Castor oil	–	20	0.1	
Chloroform	$CHCl_3$	20	nil	
Chloroacetic acid, 10%	$CH_2Cl \cdot COOH$	20	50	
Chromic acid, 20%	H_2CrO_4	20	severe	
Chromium sulfate, 5%	$Cr_2(SO_4)_3$	20	30	
Citric acid, 50%	$HOC(CH_2COOH)_2COOH$	20	42	7
Diesel oil	–	20	nil	nil

Appendix 2
Corrosion of Electroless Nickel Coatings

Test Solution	Chemical Formula	Temperature, °C	Corrosion Rate, μm/y	
			Ni-5B-5Tl	Ni-11P
Diesel oil and water suspension, 5% water	–	20	0.2	
Ethanol, 20%	CH_3CH_2OH	20	0.08	0.03
Ethylene glycol	$HOCH_2CH_2OH$	20	0.2	0.03
Formaldehyde, 30%	$HCOH$	20	13	5
Formic acid, 30%	$HCOOH$	20	36	
88%		20	90	13
Hydrochloric acid, 5%	HCl	20	severe	25
Linseed oil	–	20	0.1	
Magnesium chloride, 42%	$MgCl_2$	155	94	
Nickel acetate, 10%	$Ni(CH_3COO)_2$	20	13	
Nickel formate, 2%	$Ni(COOH)_2 \cdot 2H_2O$	20	4.7	
Oxalic acid, 1/2%	$COOH \cdot COOH$	20	18	
Phenol	C_6H_5OH	60	nil	nil
Phosphoric acid, 85%	H_3PO_4	20	severe	2
Phosphorous oxychloride	$POCl_3$	20	1	
Phosphorous thiochloride	$PSCl_3$	40	0.5	
Phosphorous trichloride	PCl_3	20	0.7	
Potassium				
carbonate, 1%	K_2CO_3	BP	nil	
5%		BP	nil	
10%		50	nil	
15%		50	nil	
20%		50	nil	0.1
saturated		BP	nil	
chlorate, 5%	$KClO_3$	20	0.9	
chromium sulfate, 10%	$K\{Cr(SO_4)_2\} \cdot 12H_2O$	20	28	
dichromate, 10%	$K_2Cr_2O_7$	20	nil	
		BP	nil	
hydroxide, 10%	KOH	20	nil	0.02
50%		20	nil	0.01
nitrate, 20%	KNO_3	BP	0.5	0.6
permanganate, saturated	$KMnO_4$	20	0.8	
		BP	1.1	
Pyridine	C_6H_5N	20	0.3	
Silicon tetrachloride	$SiCl_4$	20	0.1	
Soap, liquid, 5%	–	BP	nil	

Appendix 2
Corrosion of Electroless Nickel Coatings

Test Solution	Chemical Formula	Temperature, °C	Corrosion Rate, µm/y	
			Ni-5B-5TI	Ni-11P
Sodium				
Aluminate, 50 g/L	$NaAlO_2$	20	Nil	
		BP	nil	
Bisulfite, 5%	$NaHSO_3$	20	45	
carbonate, 1%	Na_2CO_3	50	nil	
1%		BP	nil	
5%		50	nil	
10%		50	nil	
10%		BP	nil	
15%		50	nil	
20%		20	2	0.6
saturated		50	nil	
chloride, 0.01%	$NaCl$	20	1.4	
chloroacetate, 20%	$Na(CH_2ClOO)$	20	13	
citrate, 10%	$Na_3C_6H_5O_7$	20	10	
fluoride, 10%	NaF	20	1.4	
hydroxide, 10%	$NaOH$	20	nil	0.1
45%		20	nil	0.1
phosphate, 10%	Na_3PO_4	20	nil	
		BP	nil	
sulfate, 10%	Na_2SO_4	20	11	
sulfide, 20%	Na_2S	20	0.9	nil
thiosulfate, 25%	$Na_2S_2O_3$	20	6	4
Sulfuric acid, 0.2%	H_2SO_4	20	severe	20
10%		20	severe	25
Sulfuryl chloride	SO_2Cl_2	20	2.9	
		40	1.6	
		BP	4.4	
Thionyl chloride	$SOCl_2$	20	nil	
Titanium tetrachloride	$TiCl_4$	20	0.8	
Urea, saturated	$H_2N\cdot CO\cdot NH_2$	20	0.4	1
Tartaric acid	$(CHOH\cdot CHOH)_2$	20	3.4	
Trichloroethene	$CHCl{=}CCl_2$	20	nil	nil
Turkish red oil	–	20	0.2	
Water, deionized, N_2 deaerated	–	20	nil	nil
Zinc nitrate, 20%	$Zn(NO_3)_2$	20	23	

REFERENCES

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1. G. O. Mallory, The Electroless Nickel Plating Bath, *Electroless Nickel Conference*, Products Finishing, Cincinnati, Nov 1979.

2. K. Stallman, and H. Speckhardt, Deposition and Properties of Nickel-Boron Coatings, *Metalloberflaeche Angewandte Elektrochemie*, Vol 35, No 10 (1981) p 979.

3. H. Baker, editor, *ASM Handbook, Volume 3, Alloy Phase Diagrams*, ASM International, Metals Park, Ohio, (1992), p 2•313.

4. G. G. Gawrilov, *Chemical (Electroless) Nickel Plating*, Portcullis Press Limited, Redhill, England, (1979) p 101.

5. W. Riedel, *Electroless Nickel Plating*, ASM International, Metals Park, Ohio, and Finishing Publications Limited, Hertfordshire, England, (1991) p 68-69.

6. B. Bozzini, P. Cavallotti, M. V. Ivanov, A. Buratti, and F. Krüger, "Control of Stabilizers Influence on ACD Ni-P and Ni-P-B Processes and Deposit Functional Properties", *1992 INTERFINISH Congress*, Associação Brasileira de Tratamentos de Superfície, Sao Paulo, Brazil, 5 October 1992.

7. M. Matsuoka, and T. Hayashi, *Plating and Surface Finishing*, Vol 68, No 7 (1981) p 66.

8. K. M. Gorbunova, M. V. Ivanov and V. P. Moiseev, *Journal of the Electrochemical Society*, Vol 120, (1973) p 613.

9. H. Zhang, X. J. Zhang, and Y. K. Zhang, *Plating and Surface Finishing*, Vol 80, No 4 (1993) p 80.

10. K. Masui, *Metal Finishing*, Vol 84, No 8 (1986) p 33.

11. T. V. Gaevskaya, I. G. Novotortseva and L. S. Tsybulskaya, *Metal Finishing*, Vol 94, No 6 (1996) p 100.

12. M. Matsuoka and T. Hayashi, Physicochemical Properties of Chemically Deposited Ni-B-TI Alloys, The First AES Electroless Plating Symposium, American Electroplaters' Society, St. Louis, Missouri, March 24, 1982.

13. A. T. El-Mallah, M. H. Abbas, M. F. Shafei, M. E. Aboul-Hassan, and I. Nagi, *Plating and Surface Finishing*, Vol 76, No 5 (1989) p 124.

14. Technical Bulletin, *Technical Information about Electroless or Chemical Nickel Plating by the Nibodur Method*, Paul Anke KG, Essen, Germany.

15. G. O. Mallory, *Plating*, Vol 58, No 4 (1971).

16. Helmut Kleinz, Paul Anke, KG, private communication, March, 26 and April 13, 1982.

17. G. O. Mallory, Recent Developments in Applications of Electroless Nickel Plating, National Aeronautic and Space Engineering and Manufacturing Meeting, Society of Automotive Engineers, October 6-10, 1969.

18. ASTM B 607-91, Standard Specification for Autocatalytic Nickel Boron Coatings for Engineering Use, American Society for Testing and Materials, West Conshohocken, PA, 1998.

19. K. Lang, Galvanotechnik, Vol 56 (1965) p 347.

20. M. Matsuoka and T. Hayashi, Plating and Surface Finishing, Vol 68, No 7 (1981) p 66.

21. Ronald Duncan, *Metal Finishing*, Vol 88, No 3 (1990).

22. Harold Bellis, United States Patent No. 3,674,447, July 4, 1972.

23. Lavern Weisenberger and Joseph Greene, Hardness and Wear Resistance of Electroless Nickel Alloys, *Proceedings, EN Conference '89*, Products Finishing Magazine, Cincinnati, April 4, 1989.

24. ENPLATE NI-427 Datasheet, Enthone, Inc., West Haven, CT, May 1, 1986.

25. K. Stallman, F. W. Hirth and H. Speckhardt, *Metalloberfläche Angewandte Elektrochemie*, Vol 38, No 4 (1984).

26. *Industrial Nickel Plating and Coating*, International Nickel Company, 1976.

27. Clay Graham, Hardness and Wear Implications with Respect To Electroless Nickel, *Proceedings Electroless Nickel Conference II*, Products Finishing Magazine, Cincinnati, Ohio, March 1981.

28. Gerald Smith, Value Added Benefits of Using Electroless Nickel Thallium Boron, *Proceedings, EN Conference IV*, Products Finishing Magazine, Chicago, April 23, 1985.

29. H. G. Klein, H. Niederprum and L. M. Horn, Metalloberflaeche Angewandte Elektrochemie, Vol 25, No 9 (1971) and Vol 26, No 1 (1972).

30. Ronald Duncan, Elnic, Inc., previously unpublished results.

31. ASTM Specification G-87, Standard Practice for Conducting Moist SO_2 Tests, ASTM International, West Conshohocken, PA, 1998.

Ronald N. Duncan

BIOGRAPHICAL SKETCH

In Memory of Ron Duncan

Ron Duncan served as Vice President of Palm International, Inc., where he led the company’s technical and educational initiatives. Prior to joining Palm, he was Director of Research at Elnic, Inc., focusing on electroless nickel formulation and materials research.

Before entering the metal finishing industry, Ron spent 12 years in the oil sector with Exxon and Caltex Petroleum Corporations, tackling materials and corrosion challenges. His work took him across the globe—including the United States, Middle East, Europe, South America, and Africa—where he developed a reputation for his deep expertise and practical problem-solving.

Ron held a BE in Mechanical and Metallurgical Engineering from Vanderbilt University. He was a Registered Professional Engineer and a certified Corrosion Specialist through NACE. A leader in technical standards, he chaired NACE task groups T-1G-19 and T-6A-53, contributing to authoritative reports on electroless nickel and other metallic coatings. He also served on the AESF’s Electroless Committee.

Throughout his distinguished career, Ron authored more than fifty technical papers on corrosion, coatings, and electroless nickel. His work appeared in Materials Performance, Plating and Surface Finishing, Metals Progress, Products Finishing, and Finishers Management, as well as in numerous industry conferences. He was the principal author of the electroless nickel chapter in Volume 5 of the Metals Handbook and was honored with the AESF Gold Medal in 1996 for the best paper published in Plating and Surface Finishing.

Ron also directed the Electroless Nickel School, a comprehensive four-day seminar presented by Palm, which educated professionals in all aspects of electroless nickel technology.

Ron Duncan passed away on December 15, 2006. He is deeply missed by his family, colleagues, and the broader surface finishing community. His legacy of innovation, mentorship, and integrity continues to inspire all who had the privilege of working with him.