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IMPROVED ADHESIVE BOND PERMANENCE WITH REACTIVE ORGANOSILANE COUPLING AGENTS

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Five reactive organosilane coupling agents, (Dow Corning Z6020, Z6032, Z6040, Z6062 and Union Carbide Corp. A-1100) were evaluated as adhesion promoters to improve the adhesive bond strength of 2024T3, 6061T4 aluminum alloys and 302 stainless steel and to protect the bonds against the deleterious effects of water. The organosilane coupling agents, mercaptopropyltrimethoxysilane (D.C.Z6062), and glycidoxypropyltrimethoxysilane (D.C.Z6040) generally showed better bond strength over

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initially and after adverse exposure than the control samples when bonded with room temperature-curing epoxy resin. The glycidoxypropyltrimethoxysilane (Z6040) showed better initial bond strength than the control samples and good retention of bond integrity after adverse exposure when used with aluminum alloys and an intermediate cure temperature [121°C (250°F)]epoxy adhesive. The remaining organosilanes did not show appreciable improvement over the control samples.

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INTRODUCTION

Silane coupling agents (ref 1 and 2), because of their ability to bond organic polymers to inorganic materials, can be used to improve the adhesive bonding of metals. The hydrolyzable groups on silicon are generally believed to be the means by which the silane coupling agents interact with the metallic oxides. The silanes form chemical bonds at the interface that maintain high strength under high humidity and other adverse environmental conditions. The organic moiety of the silane reacts with organic functional groups of the adhesive. Thus, the organosilane functions as a true coupling agent, bonding the inorganic metal oxide to the organic adhesive. A true coupling agent bridges the interface.

The hypothesized mechanism is:

Silane-to-Inorganic Surface Interface

1. Hydrolysis

$$R-Si(OR)_3 + 3H_2O \xrightarrow{H+} R-Si(OH_3)_3 + 3ROH$$

2. Equilibrium Bond Formation

$$\text{metal oxide} \;]\!\!- OH + \begin{matrix} HO \\ HO \\ HO \end{matrix} \!\!> Si - R \longrightarrow$$

$$]\!\!- O - \underset{\displaystyle O}{\overset{\displaystyle O}{Si}} - R + H_2O$$

Silane-to-Organic Polymer Interface

The formation of covalent bonds between the silane's organo-functional moiety and reactive species of the polymer matrix is:

$$\text{metal oxide} \;] - O - Si - R + \; [\; \text{organic resin} \longrightarrow$$

metal oxide] - O - Si - R - [organic resin

Among the more reactive organic groups available on silane coupling agents are vinyl, alkyl amino, alkyl mercapto, and epoxy radicals (table 1).

DISCUSSION OF RESULTS

In this investigation, five different reactive organosilanes (table 1) were evaluated as adhesion promoters to improve bond strength and protect the bonds against the deleterious effects of water. Initial experiments were run to determine the conditions to be used to evaluate these coupling agents. A summary of the results is given in table 2. Individual results are given in the Appendix.

1. Using a methanol wash followed by compressed air-drying of the FPL-etched specimens resulted in an improvement of approximately 10% in lap-shear tensile strength.

2. Untreated acetone-degreased specimens coated with organosilane solutions had lap-shear tensile strengths much lower than the FPL-etched control specimens.

3. Varying the concentrations (0.1, 0.5, 1.0%) of the organosilane solutions did not appreciably alter the bond strengths (table 2).

4. The method of applying the silane solution to the FPL-etched specimens (brush-on or dip) did not appreciably affect the strength of the bonds (table 2).

The amino and vinyl functional organosilanes did not show any improvement in bond strength over the control samples when 2024T3 aluminum specimens were bonded with Epon 828/Versamid 140. In several experiments they had lower bond strengths. The vinyl functional silane did not react with the epoxy group. There is some indication that aluminum specimens containing high concentrations of copper render amino functional silanes ineffective (table 2).

The mercapto and epoxy organosilanes had bond strengths 43% and 29% greater, respectively, than the control samples (Appendix). After a 34-day (816-hr), 60°C (140°F) water soak, the mercapto silane bond strength was 41% and the epoxy silane 43% better than the control water soak.

Experiments in which the organosilane was added directly to the adhesive resin indicated essentially no improvement over coating the 2024T3 aluminum adherends with silane solution initially or after a 34-day (816-hr) hot water soak (table 2). Experiments in which the mercapto silane specimens were bonded by coating the adherend and adding the silane to the resin resulted in stronger bonds than the uncoated control, however, not as strong as the bond formed by coating the adherend only. In a similar experiment using epoxy-functional silane, the bond strength was greater than the control or coating the adherend solely.

EXPERIMENTAL PROCEDURE

Preparation of Adherends

2024T3 and 6061T4 aluminum alloys were etched using the FPL etch before bonding. The panels were degreased with acetone and treated by immersing the bonding surface in a solution containing 1 part by weight (pbw) sodium dichromate, 10 pbw concentrated sulfuric acid, and 30 pbw deionized water. The solution temperature was 60°C (140°F) and the immersion time 7 to 10 minutes. The treated panels were rinsed for 1 to 2 minutes in running tap water at 60°C (140°F), rinsed with deionized water at room temperature, and dried in a circulating-air oven at 60°C (140°F). An alternate procedure for drying was also used in which the deionized water-rinsed panels were washed with absolute methanol and dried at room temperature using filtered compressed air.

Silane Primer Solution

The organosilanes were diluted to 10% pbw solids using deionized water and acidified to a pH of 3.5-5.0 with glacial acetic acid. The resulting solutions were allowed to stand 24 hours to complete hydrolysis. Silane solutions of 0.1%, 0.5%, 1.0% pbw solids were prepared by diluting aliquots with absolute methanol.

Methods of Applying Silanes

1. The diluted organosilane solutions were brushed on the metal surfaces to be bonded and dried in air.

2. The metal surfaces to be bonded were immersed in a diluted organosilane solution.

3. Neat solutions of the organosilanes were mixed in with the adhesive resin in concentrations of 0.1%, 0.5%, 1.0%.

Resins

Epon 828/Versamid 140 is a two-component epoxy adhesive system. Epon 828 is a bisphenol A epoxy resin manufactured by Shell Chemical Co., Versamid 140 is an aliphatic polyamide resin manufactured by General Mills, Inc. The latter is a combination modifier (flexibilizer) and curing agent for the adhesive system. The adhesive was formulated using 70 pbw Epon 828 and 30 pbw Versamid; it cures at 23°C (73°F) and requires approximately 0.07 MPa (10 psi) contact pressure for joint formation.

EC 2214 is a modified one-component epoxy paste manufactured by 3M Co. It is suitable at room temperature for trowel applications. It cures at 121°C (250°F) in 40 minutes. It requires only contact pressure (approximately 0.07 MPa (10 psi)) for joint formation.

Bonding Procedure

The test specimens used in this evaluation were single-lap, shear-type specimens having 12.7 x 25.4 mm (1/2 x 1 inch) bond areas. Each was fabricated in the form of four panels and the overlap was controlled by using jigs. The surfaces to be bonded were coated with organosilane solution, air dried, the adhesive was applied and the panels assembled.

Adverse Conditions

Hot water soak/residual-strength

The bonded specimens were immersed in a thermostatically controlled deionized water bath at 60°C (140°F) for 34 days (816-hr.). The specimens were then removed in a container of water at 60°C (140°F) and transferred to the test chamber of the Baldwin Tensile Test Machine which was controlled at 60°C (140°F). Each specimen was removed from the container, placed into the grips, and tested to failure at a constant load of 16.54 MPa/min.

95% relative humidity/residual strength

Specimens were conditioned in a controlled humidity cabinet of 60°C (140°F) and 95% RH for ninety days before testing.

Conversion to SI Units

Stress units of pounds per square inch (psi) were converted to megapascals (MPa) as follows:

$$\frac{psi \times 6.8948}{1000} = MPa$$

This was in accordance with ASTM E380-74.

CONCLUSIONS

Reactive organosilane coupling agents have been demonstrated to be capable of improving the initial bond strength of epoxy-based adhesives and improving the resistance of the adhesive bonds on 2024T3 and 6061T6 aluminum alloys to moisture or water-induced degradation. The adhesive and the organosilane are most effective when the organic moieties are mutually chemically reactive and the reactivity occurs during the adhesive joint formation. The vinyl functional moiety does not react with the epoxy adhesives and is ineffective in combating joint degradation. The Z6020 (2-aminoethyl) is very reactive (fumes in air); it reacts too quickly to be effective in epoxy adhesives.

RECOMMENDATION

The specificity of reactants demonstrated, the improvements gained, and the limited scope of this investigation suggest that a long range evaluation should be conducted to determine the effects of combined elevated temperature, humidity, and stress on joints with organosilane coupling agents.

REFERENCES

1. E. P. Plueddemann, "Mechanism of Adhesion of Coatings Through Reactive Silanes", Journal of Paint Technology, November 1970.

2. E. P. Plueddemann, Composite Materials: Vol. 6, Interfaces in Polymer Matrix Composites, Academic Press, 1974.

Table 1

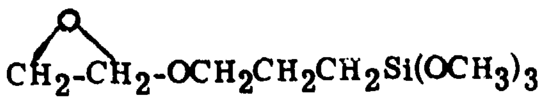
Organosilane coupling agents

Organosilanes

1. Dow Corning Z6020 - N(-2 aminoethyl)-3-aminopropyltrimethoxysilane.

   $H_2NCH_2CH_2NCH_2CH_2CH_2Si(OCH_3)_3$

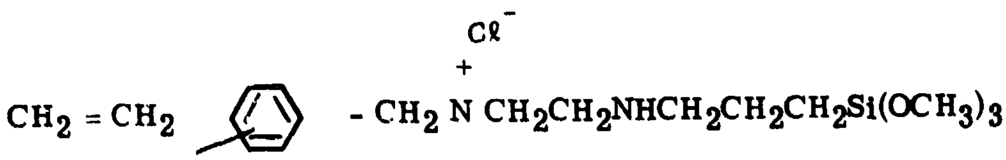
2. Dow Corning Z6040 - Glycidoxypropyltrimethoxysilane.



3. Dow Corning Z6062 - Mercaptopropyltrimethoxysilane.

   $HSCH_2CH_2CH_2Si(OCH_3)_3$

4. Dow Corning Z6032 - Vinylbenzylamine functional silane.



5. Union Carbide Corp. A-1100 - N-aminopropyltriethoxysilane.

   $H_2NCH_2CH_2CH_2Si(OCH_2CH_3)_3$

TABLE 2

SUMMARY OF ORGANOSILANE COUPLING AGENT RESULTS

ADHEREND	SILANE PRIMER	ADHESIVE	ADVERSE EXPOSURE	SHEAR STRENGTH at 21°C (70°F)		SHEAR STRENGTH ADVERSE CONDITION		% DEGRADATION
				M Pa	psi	M Pa	psi	
2024T3	none	EC2214	95% rh,	38.0	5510	28.7	4169	-24.3
(.063")			60°C(140°F)					
	Z6040	EC2214	90 days	41.8	6074	33.0	4783	-21.3
	Z6040	EC2214 / Z6040		42.1	6107	35.7	5176	-15.0
6061T4	none	EC2214	95% rh,	21.0	3054	13.2	1914	-37.3
(.063")			60°C(140°F)					
	Z6040	EC2214	90 days	25.9	3757	25.5	3696	- 1.6
	Z6040	EC2214 / Z6040		26.7	3875	28.9	4194	+ 8.
2024T3	none	Epon 828 / V-140	Hot water					
(.125")			soak, 60°C	20.9	3063	22.6	3310	+ 8.0
	Z6040	Epon 828 / V-140	(140°F)34 days	22.0	3205	27.6	4000	+24.9
6061T4 (.063")	none	Epon 828 / V-140	"	13.2	1925	9.0	1310	-41.9
	Z6040 (0.3%)	Epon 828 / V-140		26.1	3810	15.3	2243	-31.9
302	none	Epon 828 / V-140	"	10.7	1565	9.6	1395	-10.8
Stainless Steel	Z6040 (0.3%)	Epon 828 / V-140		11.5	1680	10.3	1510	-10.1

TABLE 2 (Con't)

SUMMARY OF ORGANOSILANE COUPLING AGENT RESULTS

ADHEREND	SILANE PRIMER	ADHESIVE	ADVERSE EXPOSURE	SHEAR STRENGTH at 21°C (70°F)		SHEAR STRENGTH ADVERSE CONDITION		% DEGRADATION
				MPa	psi	MPa	psi	
2024T3	none	Epon 828 / V-140	Hot water	26.9	3933	20.8	3048	-22.5
(.063")			soak, 60°C					
	Z6032 (0.3%)		(140°F)34 days	25.9	3780	20.7	3020	-20.1
6061T4	none	Epon 828 / V-140	(140°F)34 days	7.5	1090	8.1	1180	+8.3
(.063")								
	Z6032 (0.3%)			10.5	1538	9.2	1338	-13.0
302	none	Epon 828 / V-140	(140°F)34 days	23.1	3370	19.2	2800	-3.8
Stainless Steel	Z6032			21.1	3065	20.3	2948	-0.2
2024T3	none	Epon 828 / V-140	(140°F)34 days	18.2	2648	12.6	1835	-30.7
(.125")								
	Z6020 (0.5%)	Epon 828 / V-140	(140°F)34 days	20.2	2935	4.9	710	-75.9
	(Brushed on)							
	Z6020	Epon 828 / V-140	(140°F)34 days	20.8	3025	4.2	603	-80.1
	(Dipped)							
	none	Z6020		19.1	2778	12.7	1845	-33.6
	Z6020	Z6020		14.5	2180		No Bond	-100.0

TABLE 2 (Con't)

SUMMARY OF ORGANOSILANE COUPLING AGENT RESULTS

ADHEREND	SILANE PRIMER	ADHESIVE	ADVERSE EXPOSURE	SHEAR STRENGTH at 21°C (70°F)		SHEAR STRENGTH ADVERSE CONDITION		% DEGRADATION
				M Pa	psi	M Pa	psi	
2024T3	none	Epon 828 / V-140	Hot water	20.5	2978	11.1	1625	-45.4
(.125")			Soak, 60°C					
	Z6062 (0.5%)		(140°F)34 days	29.3	4255	15.6	2270	-46.7
	none	+Z6062	(140°F)34 days	22.0	3200	14.4	2095	-34.5
	Z6062	+Z6062	(140°F)34 days	23.6	3420	18.0	2610	-23.7
2024T3	none	Epon 828 / V-140	(140°F)34 days	19.2	2793	15.5	2245	-19.6
(.125")								
	Z6040 (0.5%)	Epon 828 / V-140	(140°F)34 days	24.8	3598	22.0	3190	-11.3
	none	Z6040		27.4	3978	13.9	2015	-49.3
	Z6040	Z6040		28.0	4080	25.5	3585	-12.1
2024T3	none	Epon 828 / V-140		26.0	3778	11.0	1605	-57.5
(.125")								
	A-1100	Epon 828 / V-140		18.9	2745	8.4	1221	-55.5
	(1.0%)							
2024T3	none	Epon 828 / V-140		25.7	3728	11.4	1673	-55.1
(.125")								
	Z6062 (1.0%)	Epon 828 / V-140		26.1	3793	12.5	1822	-52.0

APPENDIX

EFFECTS OF FUNCTIONAL COUPLING AGENTS ON BOND STRENGTHS

Effect of Epoxv Functional Coupling Agents on Bond
Strengths to 2024T3 Aluminum with EC 2214

ADHEREND	SILANE PRIMER	ADHESIVE	ADVERSE EXPOSURE	SHEAR STRENGTH AT 21° (70°F)		SHEAR STRENGTH ADVERSE CONDITION		% DEGRADATION	
			psi	psi	M Pa	psi	psi	M Pa	
2024T3	none	EC 2214	5557			4324			
(.063")			5857			4196			
			5292			4304			
			5592			4091			
			5744			3928			
			5020	5510	38.0		4169	28.7	
	Z6040	EC 2214	5783			4793			
			6134			4884			
			6155			4781			
			6241			4859			
			6421			4600			
			5709	6074	41.8		4783	33.0	
	Z6040	EC 2214 / Z6040	5876			5354			
			6358			5540			
			6118			5053			
			5885			5025			
			6270			4905			
			6136	6107	42.1		5176	35.7	

Effects of Epoxy Functional Coupling Agent on Bond Strengths to 6061T4 Aluminum with EC 2214

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 95th 21°C (70°F)	AVG		60°C (140°F)	AVG		
			psi	psi	M Pa	psi	psi	M Pa	
6061T4	none	EC 2214	2880			1959			
(.063")			3255			1869			
			3159			1796			
			2892			1963			
			3215			1984			
			2923	3054	21.0		1914	13.2	
	Z6040	EC 2214	3697			3709			
			3964			3592			
			3745			3687			
			3909			3767			
			3702			3724			
			3507	3757	25.9		3696	25.5	
	Z6040	~~EC 2214~~ Z6040	3788			4302			
			3909			4096			
			4052			4240			
			3729			4188			
			3866			4172			
			3908	3875	26.7		4194	28.9	

Effects of Epoxy Functional Coupling Agent on Bond Strengths to 2024T3 Aluminum with Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)		AVG	Hot Water Soak 60°C (140°F) 34 days		AVG	
			psi	psi	M Pa	psi	psi	M Pa	
2024T3	none	Epon 828 / V-140	3340			3440			
(.125")			2900			3400			
			3060			3300			
			2950	3063	20.9	3100	3310	22.6	
	0.3%								
	Z6040	Epon 828 / V-140	3100			3940			
	Brushed		3240			3900			
	on		3200			4080			
			3280	3205	22.0	4100	4005	27.6	

Effects of Epoxy Functional Coupling Agents on Bond Strengths to 6061T4 Aluminum with Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F) psi	21°C (70°F) AVG psi	21°C (70°F) AVG M Pa	Hot Water Soak 60°C (140°F) 34 days psi	Hot Water Soak AVG psi	Hot Water Soak AVG M Pa
6061T4	none	Epon 828 / V-140	1760			1200		
			2100			1400		
			1740			1340		
			2100	1925	13.2	1300	1310	9.0
	0.3%							
	Z6040	Epon 828 / V-140	3540			2520		
	Brushed on		4000			2000		
			3760			2400		
			3920	3810	26.1	2050	2243	15.3

Effects of Epoxy Functional Coupling Agent on Bond Strengths to 302 Stainless Steel Using Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)			SHEAR STRENGTH Hot Water Soak 60°C (140°F) 34 days			
				AVG			AVG		
			psi	psi	M Pa	psi	psi	M Pa	
302	none	Epon 828 / V-140	1690			1560			
Stainless			1710			1500			
Steel			1730			1460			
			1590	1680	11.5	1520	1510	10.3	
	0.3%								
	Z6040	Epon 828 / V-140	1460			1380			
	Brushed on		1520			1420			
			1600			1360			
			1680	1565	10.7	1420	1395	9.6	

Effects of Vinyl Functional Coupling Agent on Bond Strengths to 2024T3 Aluminum with Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F) psi	21°C (70°F) AVG psi	21°C (70°F) AVG M Pa	Hot Water Soak 60°C (140°F) 34 days psi	Hot Water Soak AVG psi	Hot Water Soak AVG M Pa	
2024T3	none	Epon 828 / V-140	3710			2900			
(.063")			3750			3000			
			3820			2980			
			3800	3780	25.9	3200	3020	20.7	
	0.3%								
	Z6032	Epon 828 / V-140	3970			2960			
	Brushed on		3870			3000			
			3910			3050			
			3980	3933	26.9	3180	3048	20.8	

Effects of Vinyl Functional Coupling Agents on Bond Strengths to 6061T4 Aluminum with Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)	21°C (70°F) AVG		Hot Water Soak 60°C (140°F) 34 Days	60°C (140°F) 34 Days AVG		
			psi	psi	M Pa	psi	psi	M Pa	
6061T4	none	Epon 828 / V-140	1210			1130			
(.063")			1000			1100			
			1100			1250			
			1050	1090	7.5	1240	1180	8.1	
	0.3%								
	Z6032	Epon 828 / V-140	1500			1300			
	Brushed on		1560			1400			
			1580			1300			
			1510	1538	10.5	1350	1338	9.2	

Effects on Vinyl Functional Coupling Agents on Bond Strengths to 302 Stainless Steel using Epon 828 Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)		AVG	Hot Water Soak 60°C (140°F) 34 Days		AVG	
			psi	psi	M Pa	psi	psi	M Pa	
302	none	Epon 828 / V-140	3360			2900			
Stainless			3520			2760			
Steel			3200			2800			
			3400	3370		2750	2803	19.2	
	0.3%								
	Z6032	Epon 828 / V-140	2960			2930			
	Brushed		3160			3040			
	on		3560			2970			
			2580	3065	21.1	2850	2948	20.3	

Effects of Diamino Functional Coupling Agent on Bond Strengths to 2024T3 Aluminum using Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F) psi	21°C (70°F) AVG psi	21°C (70°F) AVG M Pa	Hot Water Soak 60oC (140°F) 34 days psi	AVG psi	AVG M Pa	
2024T3	none	Epon 828 / V-140	2700			1800			
			2500			2000			
			2630			1640			
			2760	2648	18.2	1900	1835	12.6	
	.5%								
	Z6020	Epon 828 / V-140	2930			730			
	Brushed		2900			660			
	on		2950			730			
			2960	2935	20.2	720	710	4.9	
	Z6020		2960			600			
	Dipped into		2900			500			
	Silane		3150			650			
	Solution		3090	3025	20.8	660	603	4.2	
	none	1% Z6020	2790			1730			
			2810			1860			
			2760			1940			
			2750	2778	19.1	1850	1845	12.7	

ADHEREND	SILANE PRIMER	ADHESIVE	21°C (70°F)	AVG		SHEAR STRENGTH Hot Water Soak 60°C (140°F) 34 days	AVG		
			psi	psi	M Pa	psi	psi	M Pa	
	Z6020	1% Z6020	2090			Broke in handling			
			2130			Broke in handling			
			2130			200			
			2080	2108	14.4	200			

Effects if Mercapto Functional Coupling Agent on Bond
Strengths to 2024T3 Aluminum using Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)		AVG	Hot Water Soak 60°C (140°F) 34 days		AVG	
			psi	psi	M Pa	psi	psi	M Pa	
2024T3	none	Epon 828/V-140	2810			1630			
			2900			1630			
			3100			1560			
			3100	2978	20.5	1680	1625	11.1	
	.5%								
	Z6062	Epon 828/V-140	4250			2220			
	Brushed		4270			2300			
	on		4140			2320			
			4360	4255	29.3	2240	2270	15.6	
	none	1% Z6062	3100			2060			
			3100			1980			
			3300			2160			
			3300	3200	22.0	2180	2095	14.4	
	Z6062	1% Z6062	3400			2620			
			3450			2580			
			3410			2580			
			3420	3420	23.6	2660	2610	18.0	

Effects of Epoxy Functional Coupling Agent on Bond Strengths to 2024T3 using Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)	AVG		Hot Water Soak 60°C (140°F) 34 days	AVG		
			psi	psi	M Pa	psi	psi	M Pa	
2024T3	none	Epon 828 / V-140	2860			2120			
(.125")			2730			2260			
			2780			2280			
			2800	2793	19.2	2320	2245	15.5	
	.5%								
	Z6040	Epon 828 / V-140	3520			3120			
	Brushed on		3320			3100			
			4000			3140			
			3550	3598	24.8	3400	3190	22.0	
	none	1% Z6040	3860			2000			
			4130			2100			
			3990			1960			
			3930	3978	27.4	2000	2015	13.9	
	Z6040	1% Z6040	4060			3540			
			4070			3540			
			4050			3580			
			4140	4080	28.0	3560	3585	25.5	

Effects of Amino Functional Coupling Agents on Bond Strengths to 2024T3 Aluminum with Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)			Hot Water Soak 60°C (140°F) 34 days			
				AVG			AVG		
			psi	psi	M Pa	psi	psi	M Pa	
2024T3	none	Epon 828 / V-140	3580			1610			
			3780			1620			
			3750			1590			
			4000	3778	26.0	1600	1605	11.0	
	1%								
	A-1100	Epon 828 / V-140	2800			1260			
	Brushed on		2700			1215			
			2720			1190			
			2760	2745	18.9	1220	1221	8.4	

Effects of Mercapto Functional Coupling Agent on Bond Strengths to 2024T3 Aluminum using Epon 828/Versamid 140

ADHEREND	SILANE PRIMER	ADHESIVE	SHEAR STRENGTH 21°C (70°F)	AVG		Hot Water Soak 60°C (140°F) 34 days	AVG	
			psi	psi	M Pa	psi	psi	M Pa
2024T3	none	Epon 828 / V-140	4000			1625		
(.125")			3560			1700		
			3550			1725		
			3800	3728	25.7	1640	1673	11.4
	1%							
	Z6062	Epon 828 / V-140	3700			1750		
			3720			1900		
			3800			1825		
			3950	3793	26.1	1810	1822	12.5

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