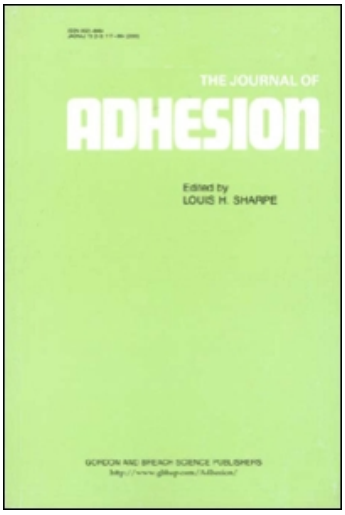

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Adhesive Bonding to Galvanized Steel: I. Lap Shear Strengths and Environmental Durability

Robert T. Foster[a]; Kevin J. Schroeder[a]
[a] Polymers Department, General Motors Research Laboratories, Warren, Michigan, USA

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Adhesive Bonding to Galvanized Steel

I. Lap Shear Strengths and Environmental Durability

ROBERT T. FOISTER and KEVIN J. SCHROEDER

Polymers Department, General Motors Research Laboratories, Warren, Michigan 48090, U.S.A.

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Initial (*i.e.*, unaged) adhesion, as well as adhesion after seven day, 60°C water immersion and six week scab corrosion accelerated environmental exposures, has been assessed for five different one and two-part epoxy adhesives, bonded to three different types of galvanized steel substrates. We have shown that adhesion, as measured by lap shear strength, is specific to the galvanized substrate type. In general, for a given adhesive, adhesion to "hot-dipped" galvanized substrates is harder to achieve and maintain under accelerated environmental exposure than is adhesion to "electroplated" galvanized. Also, for a given type of galvanized steel, the one-part epoxies evaluated generally showed higher initial strengths, as well as better strength retention under environmental exposure than did the two-part epoxies.

KEY WORDS Lap shear strengths; environmental durability; galvanized substrates; corrosion; one and two part epoxies; structural adhesives.

INTRODUCTION

With long-term product durability goals has come increased scrutiny of coated metals, chiefly galvanized steel, for use in automotive applications. While in principle the benefits in corrosion protection to be obtained using galvanized steel are clear, at the same time

concerns in cost, processing, and product quality must be addressed. For example, the increased cost of galvanized compared to base sheet steel, coating integrity in forming and stamping processes, weld tip maintenance, corrosion due to loss of coating near weld spots, ability to prime and paint the coated metal, and the ability to bond galvanized steel structures adhesively are all legitimate concerns which require estimation of their overall impact.

With the exception of several references noted below, there has been little work on bonding to the various types of galvanized steel currently available. In this context, the purpose of this work has been to characterize, in a systematic fashion, the relative adhesion and environmental durability of structural adhesive bonds to galvanized steel. Three different types of galvanized steel, including "ultrasmooth" and "minimum spangled" hot-dipped, together with electroplated, have been bonded with five different epoxy adhesives. Both one- and two-part epoxies were used, and the various substrates were either "cleaned" (solvent-wiped) or "oiled" (solvent-wiped, followed by dipping in a light mineral seal oil, which is a straight cut from a petroleum distillate, with no additives) prior to bonding. In reporting our work we have divided the results and their discussion into two separate parts. Part I, which constitutes this paper, is concerned with the relative adhesion and environmental durability of the various systems above, as can be assessed from values of initial lap shear strength, strength retention after seven day, 60°C immersion in de-ionized water, and three and six week "scab corrosion" cycling. Part II[1] is an in-depth investigation of lap shear failure modes (initial, and after environmental exposure), and failure surface chemistry.

We have not attempted to complete an experimental matrix encompassing all test environments for all five adhesives on each of the three substrates (both cleaned and oiled). Nonetheless, although necessarily limited in terms of the number of different adhesives, substrates, substrate preparations (*e.g.*, coating with other metal-working lubricants encountered in automotive production is not included), and accelerated testing environments, the systems employed in this work are representative enough to establish the major problems, peculiarities, and future directions which are important in structural adhesive bonding to galvanized steel.

EXPERIMENTAL

Materials

The epoxy adhesives used in this work included one unfilled two-part system, two commercial one-part systems, and two commercial two-part systems. The unfilled two-part formulation, designated EA2, is the result of previous work in bonding to primers electrodeposited on steel substrates.[2,3,4] The commercial systems represent a sampling of typical adhesives for automotive structural bonding. A list of these adhesives and comments is given in Table I.

Three different galvanized steel substrates, two hot-dipped products and one electrogalvanized product, were investigated and are listed in Table II.

Lap shear adhesive samples

Standard single lap shear samples, 25.4 × 101.6 mm, were prepared essentially in accordance with ASTM D1002. In general, however, the metal gauge of the substrate material was thinner than that specified in this test method (see Table II). All samples were washed with acetone prior to adhesive application. Samples with no further preparation are designated "cleaned". To simulate, in a

TABLE I
Adhesives

Designation†	Type	Remarks
EA2	Two-Part Epoxy	Imidazole-Cured, Modified Epoxy Novolac
H2071	Two-Part Epoxy	Amine-Cured Epoxy; 1:1 (by weight) Catalyst/Resin Mix Ratio
H5188	Two-Part Epoxy	Triethylenetetramine-Cured Epoxy; 1:17 Mix Ratio
H1989	One-Part Epoxy	Latent Catalyst (dicyandiamide)-Cured Epoxy
O1055	One-Part Epoxy	Latent Catalyst (dicyandiamide)-Cured Epoxy

† These are coded designations for the adhesives investigated. The authors may be contacted regarding their specific identity.

interactions, they cannot be related to the nature or character of the original mating interface. The suggestion that ε_c may be associated with the nature of the original mating surface is consistent with the definition of this term and with the fact[1] that failure always occurs at or near the original interface of the weld.

The shear modulus of the CAL of the MEK and the CYH jointing systems could be calculated using the expression for l_c, while the ε_c values could be calculated using equation (2). The G and ε_c values for the THF jointing system could not be determined in the above manner since only data for 20 mm overlap specimens were available. However, an estimate of the ε_c value of the THF specimens could be obtained from Eq. (1) by assuming that G (THF) was equal to G (MEK) and neglecting the effect of adherend bending on the experimental data. Hence, an overestimate of G (THF) was utilized since the micro-hardness of the THF weld ($8.4\,\text{mm}^{-1}$) was actually smaller than that of the MEK weld ($9.6\,\text{mm}^{-1}$). The use of the assumed value of G (THF) and the neglect of the effects of adherend bending would yield an underestimate of the real value of ε_c for the THF jointing system. The calculated values of ε_c and G, and the experimental values of η are as shown in Table II.

From Table II, it can be seen that the calculated value of G (CYH) is lower than the value of G (MEK), consistent with the micro-hardness results. The ε_c values of the CYH and the THF jointing systems are obviously larger than the ε_c value of the MEK system (see Table II). A large ε_c value probably implies a strong

TABLE II
Values of the three independent parameters and of the first and second terms in Eq. (1) for the different solvent weld systems

Bonding solvent	η (mm)	G (MPa)	ε_c	First term $\left[\frac{G\eta S_1 S_2}{S_1 + S_2}\right]^{1/2}$	Second term $\frac{\varepsilon_2(2+\varepsilon_c)}{1+\varepsilon_c}$
MEK	0.52 ± 0.08	6.60 (±25%)	0.13 (±29%)	1.10	0.25
CYH	0.12 ± 0.03	1.42 (±33%)	0.68 (±37%)	0.28	1.08
THF	0.54 ± 0.06	6.60[a]	0.17[b]	1.12[b]	0.32[b]

[a] G (THF) assumed to be equal to G (MEK).
[b] Calculation based on assumed value of G (THF).

systematic fashion, the minimum surface contamination expected on production substrates, "oiled" samples were dipped in Texaco AL-MAG 1564 mineral seal oil following the acetone wash, and suspended vertically for at least eight hours. Those samples designated as "Oiled/ELPO" were oiled, bonded with the designated adhesive, then primed with ED 3150A cathodic electrodeposition ("ELPO") primer (PPG Industries). All lap shear specimens were made with a 12.7 mm bond overlap 0.127 mm bond thickness, except for the samples prepared with the H2071 two-part adhesive. In this case, due to the viscosity of this highly-filled adhesive, a 0.51 mm bond thickness was employed. In both cases bondline thicknesses were maintained by incorporating a piece of copper wire of the appropriate dimension. Samples were assembled using a bonding fixture designed to give a constant 100 kPa clamping pressure. The fixture was heated to the cure temperature before lap shear assembly. Lap shear strengths were then determined by testing the specimens on an Instron (Model TTC) test machine using a crosshead speed of 1.27 mm/minute. Mean lap shear strengths (average of five samples) were calculated from the maximum loads recorded prior to bond rupture.

Adhesive cure: No ELPO

Initial cure employing the H2071 two-part adhesive was obtained by allowing the samples to remain in the bonding fixtures, at ambient temperature, for approximately twelve hours. The remaining adhesives were given an initial, elevated temperature cure by heating at 200°C in a forced air oven for twenty-five minutes. All samples were then post-cured through the following cycle which simulates a typical automotive paint bake process.

1) 75 minutes at 160°C.
2) Cold tap water quench.
3) 30 minutes at 135°C.
4) 45 minutes cooling at room temperature.
5) 20 minutes at 135°C.
6) 45 minutes cooling at room temperature.
7) 40 minutes at 160°C.

Adhesive cure: ELPO

In a typical automotive production sequence, bonded structures are generally subjected to subsequent priming (the "ELPO" process) and heat-cycling during painting. The influence of the ELPO-primer was assessed for two adhesives using samples prepared as follows. Lap shear samples bonded with the EA2 adhesive were given an initial cure of thirty minutes at 150°C, then ELPO-primed. Those bonded with H2071 two-part, however, were allowed to cure for approximately twelve hours at room temperature before priming. Following initial cure and subsequent priming, they were post-cured through the simulated paint-bake cycle outlined above.

Environmental exposures

"Initial strength" samples were tested after an overnight exposure to ambient conditions, following the paint-bake cycle. "Water immersion" samples were soaked for seven days in a constant temperature, deionized water bath maintained at 60°C. "Scab corrosion" samples were exposed to either 15 ("three week") or 30 ("six week") cycles of the following:

1) 22.5 hours at 49°C, 85% relative humidity.

2) 0.25 hours immersion in 5% NaCl solution at room temperature.

3) 1.25 hours open air dry at room temperature.

4) On weekends the samples were stored at 49°C and 85% relative humidity.

Testing of all environmentally exposed samples was completed within two hours after removal from environment to minimize recovery effects. Average percent strength retention after environment was calculated with respect to average initial strengths. Standard deviations for these average strength retention values were calculated using the appropriate "propagation of errors" formulae.[5]

RESULTS AND DISCUSSION

The bonding substrates

Both the ultrasmooth and minimum spangled substrates are the result of a "hot-dipping" process, where suitably prepared sheet

steel is drawn through a molten bath consisting primarily of zinc, but also with traces of other metals such as aluminum, magnesium, lead, and cadmium[6] present. Oxides of these trace metals may often constitute a major proportion of the outermost surface layer ($\leq$50 Å), however.† In contrast, electrodeposited zinc ("electroplated") layers are virtually pure zinc, with zinc oxide as the entire surface layer. As a result of the different processes for zinc plating, surface roughness generally varies from ultrasmooth, which (as its name implies) is quite free of large scale roughness, to minimum spangled, with isolated roughness, to electroplated, which consists of a closely-packed layer of plate-like crystals. In addition, as shown in Table II, coating thickness as well as the thickness of the underlying steel sheet may vary. Consequently, each of these characteristics separately, or together, may influence initial adhesive strength and/or durability. It is in fact the goal of this paper to identify significant differences in shear strengths, durabilities, and trends in these quantities, which would, in normal testing, be attributable to differences in adhesive and/or substrate type. For example, it has previously been demonstrated by Ziane *et al.*,[7] that there is a strong interaction between the bonding surface, as characterized by surface pretreatment, or lack thereof, and resultant bond strength for hot-dipped galvanized substrates.

Comparison of lap shear strengths and strength retention

The discussion of lap shear and durability results below can be followed by reference to the corresponding figure designated in the text. For a given adhesive, lap shear strength and durability in these figures is shown in bar graph form. The calculated mean value is shown as a horizontal bar within a shaded area, which corresponds to +/− the calculated standard deviation.

Initial strengths With reference to Figure 1, initial lap shear strength generally increases (for four of the five adhesives) as substrate type is changed in the order ultrasmooth $\lesssim$ minimum spangled $<$ electroplated. For the EA2 two-part epoxy, for example, the initial strength essentially doubled (mean strength =

† An in-depth discussion of galvanized steel surface chemistry and its relationship to adhesive bond strength and durability is given in Ref. 1.

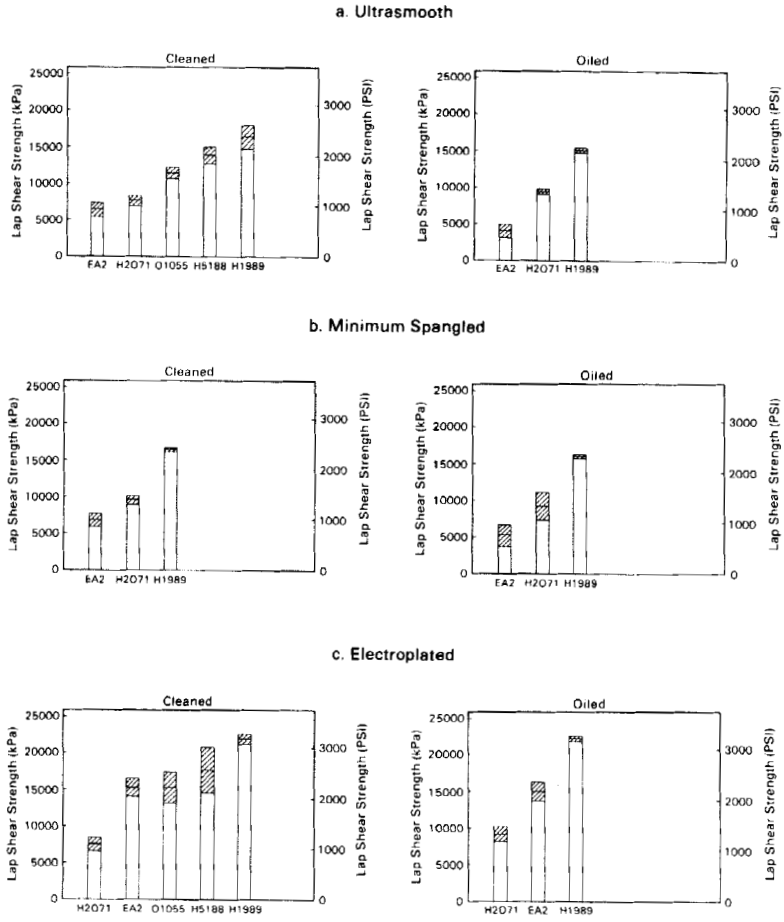

FIGURE 1 Initial lap shear strength: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated. Shaded portions correspond to standard deviations.

6500 kPa on cleaned ultrasmooth, mean strength = 15,200 kPa on cleaned electroplated). The commercial two-part, H2071, in contrast, showed little variation of mean strength with substrate (7700 kPa on cleaned ultrasmooth, to 7500 kPa on cleaned electroplated). However, for the initial strength samples, the failure mode for H2071 was

always cohesional, *i.e.* within the adhesive itself. The highest initial strength for a two-part was for H5188, which gave 13,800 kPa on cleaned ultrasmooth and 17,500 kPa on cleaned electroplated.

Initial strengths for the one-part commercial epoxies H1989 and 01055 were consistently high on all substrates, ranging from approximately 13,800 kPa on cleaned ultrasmooth to approximately 20,700 kPa on cleaned electroplated.

As can also be seen graphically in Figure 1, in all cases there was little significant difference in initial strength for cleaned *versus* oiled samples. This is in accord with previous work[8] in this laboratory on bonding to mild steel substrates oiled with this same mineral seal oil. It also accords with the recent work of Commerçon and Wightman.[9] It should be emphasized, however, that in general the initial strength is expected to be sensitive to the nature of the surface contaminant, as well as the underlying substrate. Thus, care should be taken in inferring a general behavior for all types of contaminant including other metal-working lubricants, from data for the mineral seal oil alone.

Strengths and strength retention after seven day, 60°C water immersion As can be seen in Figures 2 (lap shear strengths) and 3 (retention), all bonds lost strength during seven-day, 60°C water immersion accelerated testing. In the worst cases, on ultrasmooth and minumum spangled substrates, EA2 and H2071 gave low residual strengths (≤3500 kPa) and strength retention (≤50%). There were higher strengths (~10,300 kPa) and strength retention values (~70%) observed for EA2 on electroplated. The commercial two-part H2071, however, showed no comparable trend. In addition, this system failed at or near the adhesive/substrate interface (*i.e.* "adhesionally") after immersion.[1] Again, the highest residual strengths (7200 kPa on cleaned ultrasmooth; 1700 kPa on cleaned electroplated) and retention (52% on cleaned ultrasmooth; 95% on cleaned electroplated) of the two-part epoxies, were recorded for H5188.

Paralleling the trends in initial strengths discussed above, the one-part epoxies H1989 and 01055 generally gave higher residual strengths and retained a greater percentage of their strengths, than did the two-part systems. For example, as can be seen from Figure

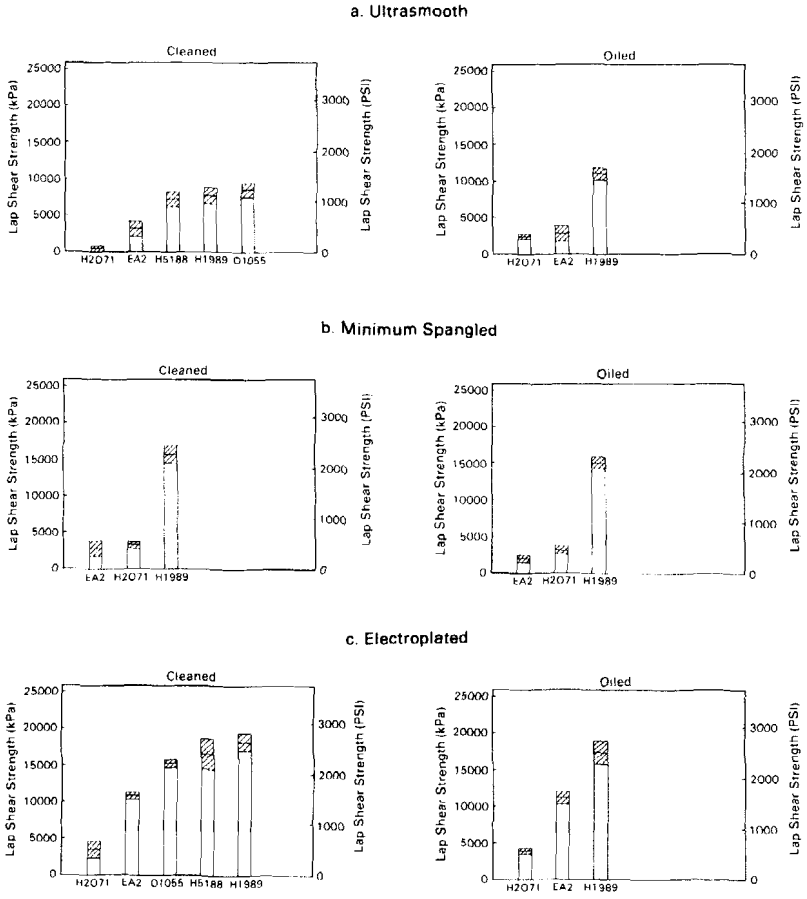

FIGURE 2 Lap shear strength after 7-day, 60°C water immersion: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated. Shaded portions correspond to standard deviations.

3, strength retention for these adhesives was generally better than 70% on all substrates. The only exception (see Figure 3a) was for H1989 on cleaned ultrasmooth (48%), which is essentially equivalent to that for the two-part H5188 (52%).

We also note that in some cases greater residual strengths and strength retention values were recorded for a given adhesive on the

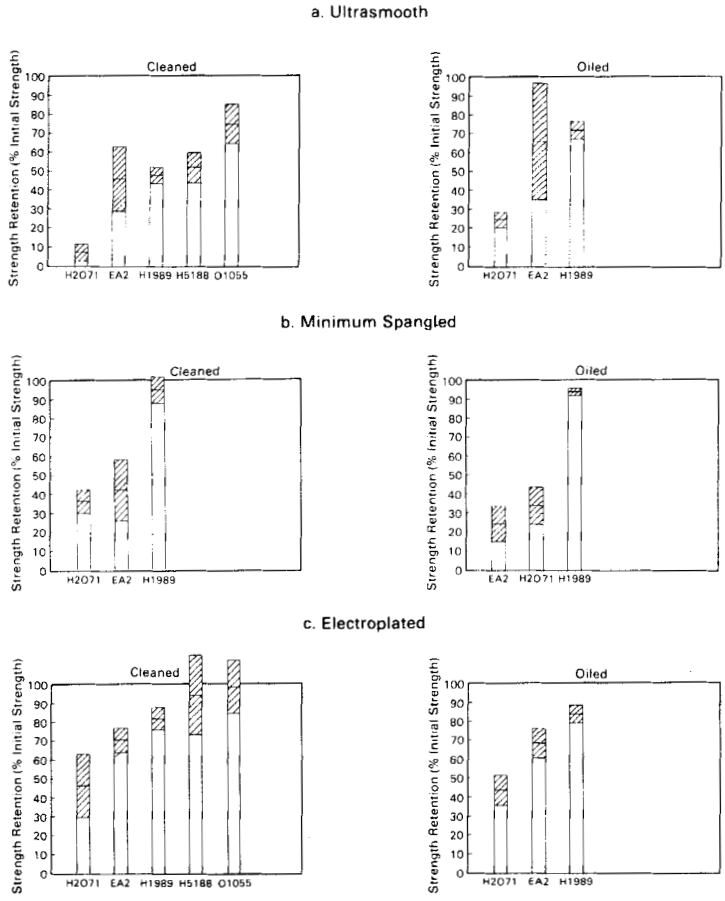

FIGURE 3 Strength retention after 7-day, 60°C water immersion: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated. Shaded portions correspond to standard deviations.

oiled than on the cleaned substrate.† Several specific examples can be cited: H2071, H1989, and EA2 on ultrasmooth substrates

† Studies of the "activation energy" of adhesion loss, currently underway in this laboratory, indicate that strength loss in a moist environment proceeds *via* a different mechanism for oiled than for cleaned metallic substrates. The evidence available thus far suggests that water immersion at 60°C accelerates strength loss at a slower rate for oiled, than for cleaned metal substrates. However, at lower temperatures, the reverse trend has been observed.

(Figure 3a). As was the case for the initial strengths discussed above, residual strengths and strength retention values generally (with due note to the exceptions just cited) showed little significant difference between cleaned and oiled substrates.

Strengths and strength retention after scab corrosion cycling Generally, bond strength decreases with time (or number of cycles) in the scab corrosion environment. Interestingly, in general a rough equivalence between strength retention after seven day, 60°C water immersion and three weeks (15 cycles) in scab corrosion was apparent from the data. However, it should be emphasized that the mechanism of strength loss is quite different for the two accelerated testing environments. Formation of a basic zinc chloride salt at the adhesive/substrate interface, for example, accompanies debonding in scab corrosion.[1]

From Figures 4, 5 and 6, it is apparent that the two-part epoxies EA2 and H2071 have the lowest residual strengths and retention values on all of the three galvanized substrates. In fact, in three weeks H2071 essentially loses all strength on (cleaned and oiled) ultrasmooth and minimum spangled substrates (Figure 5a, 5b). On oiled electroplated substrates, H2071 retains 44% of its initial strength after three weeks, but loses essentially all strength after three more weeks (30 total cycles) (Figure 5c). The two-part EA2 is somewhat better, although the general trends indicated in Figure 4, and especially Figure 5, point toward increased strength loss with continuing exposure. Data available for the remaining two-part, H5188, suggest that this system exhibits better performance than the other two-parts, as was the case for initial strengths and for strength retention after water immersion. In scab corrosion cycling, as can be seen particularly in Figures 4a and 5a, the performance of this two-part is, taking into account statistical scatter in the data, as good as the one-part H1989. The "rough equivalence" to H1989 indicated by the results for water immersion, therefore holds for scab corrosion cycling as well. This equivalence is also illustrated in Figure 6, which incorporates the calculated standard deviation into the bar graph for strength retention.

As was the case for water immersion, the performance of the one-parts (considering strengths, as well as strength retention values) is generally better in scab corrosion than the two-parts. The

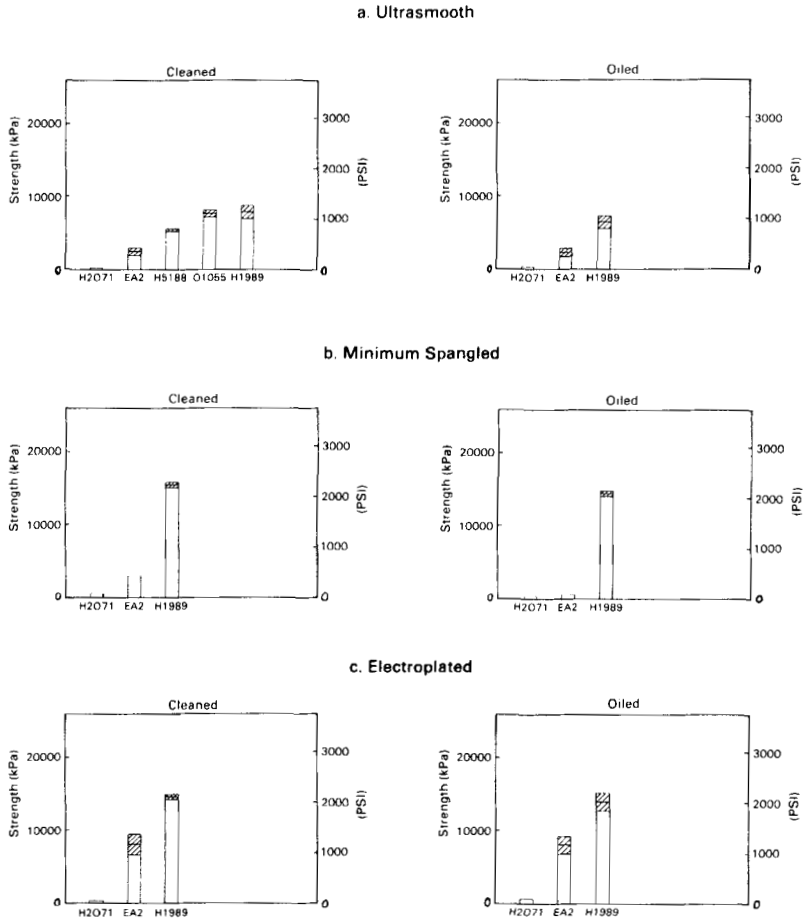

FIGURE 4 Lap shear strengths after 6-week scab corrosion cycling: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated. Shaded portions correspond to standard deviations.

H1989 system, in fact, retained some 90% of its initial strength after six weeks (30 cycles) in scab corrosion, when minimum spangled galvanized was used as the bonding substrate (Figure 6b). When bonded to this same substrate the two-parts EA2 and H2071, on the other hand, showed significant strength loss after an equivalent exposure time.

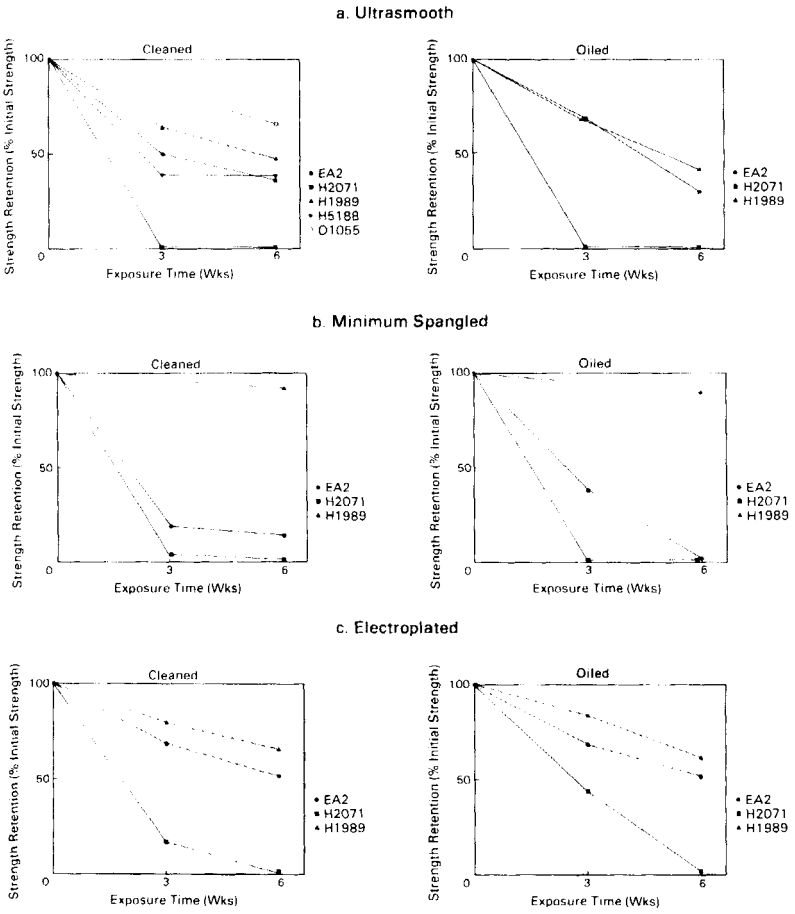

FIGURE 5 Strength retention *versus* exposure time in scab corrosion cycling: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated.

In the way of general trends, the scab corrosion data indicate that, in agreement with the discussion above, ultrasmooth and minimum spangled substrates are more susceptible to bond degradation than electroplated substrates. Also, with the exception of H2071 on electroplated galvanized (three-week exposure), for the conditions tested there were no significant differences in strength or

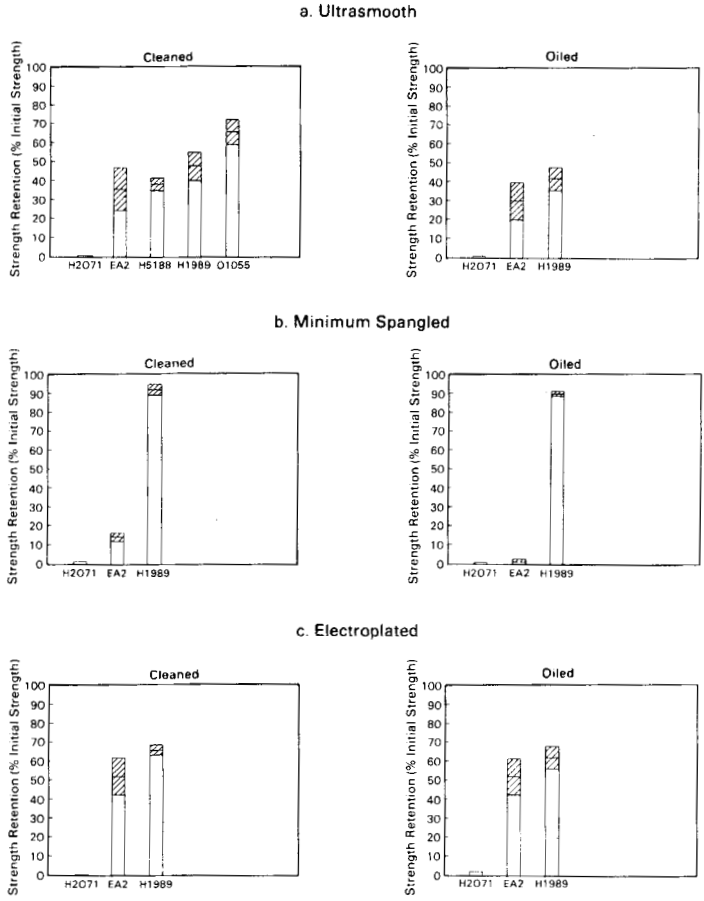

FIGURE 6 Strength retention after 6-week scab corrosion cycling: Variation with galvanized substrate type. a) ultrasmooth, b) minimum spangled, c) electroplated. Shaded portions correspond to standard deviations.

strength retention between cleaned and oiled substrates for a given adhesive.

Effects of ELPO-priming after bonding For the EA2 and H2071 two-part epoxies on oiled ultrasmooth galvanized substrates, the effects of ELPO-priming on initial strengths after bonding are, as

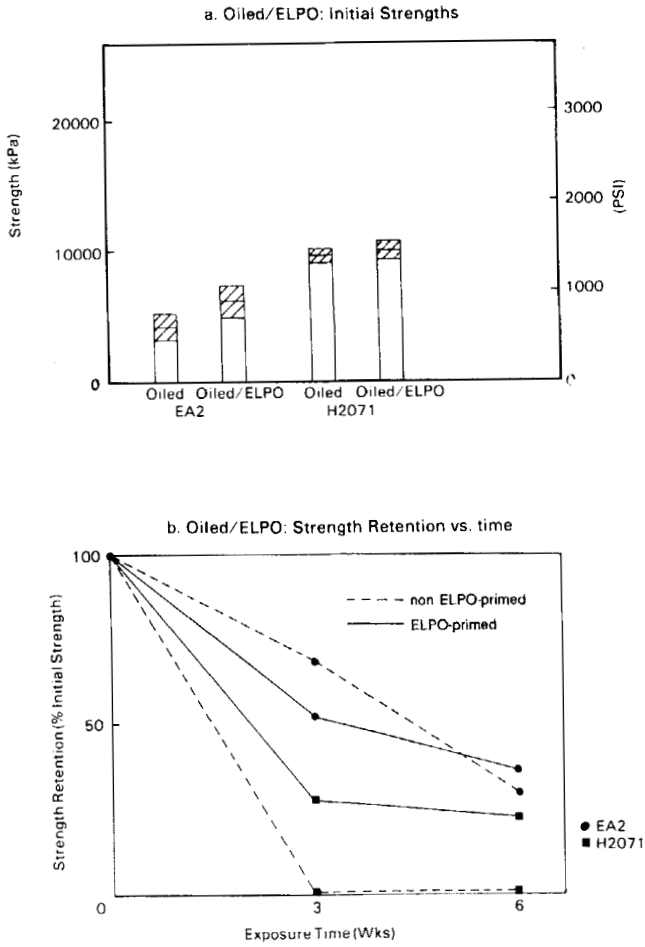

FIGURE 7 Effect of ELPO-prime after bonding: Oiled ultrasmooth galvanized. a) initial strengths, b) strength retention *versus* time in scab corrosion.

expected, negligible (Figure 7a). The effect of ELPO-priming is, however, significant for the H2071 system subjected to scab corrosion cycling (Figure 7b). Where the non-ELPO-primed system (the dotted line) lost all strength before, or by, the three-week exposure, some 28% (three weeks) and 22% (six weeks) of initial strength was retained when initial cure was followed by priming (the

solid line). This improvement is most probably due simply to the ability of the primer to retard the rate of moisture/salt solution ingress into the bond. Thus strength loss, which directly reflects the amount of delamination resulting from corrosion ingress, is retarded as well. Although the results for EA2 on oiled ultrasmooth galvanized are not as dramatic as for H2071, the ELPO-primed samples appear to show a decrease in the *rate* of strength loss with increasing exposure time (the solid line). The non-primed samples show an approximately constant rate with increasing exposure time (the dotted line). Although further work is needed to validate these trends, if these observations are qualitatively correct, the underlying reason is again a decrease in the rate of moisture/salt solution ingress resulting from the protection of the primer.

Comparison of strengths, strength retention—Miscellaneous substrates It is instructive to compare lap shear strengths and strength retention data for several of the adhesives on galvanized steel with analogous data on other substrates. To make such a comparison meaningful, we must take into account that substrate thickness can influence lap shear strengths *via* introduction of varying degrees of peel stress during single lap shear tensile testing.[10] Since the galvanized substrates were thinner than the normal recommended thickness for ASTM D1002, for comparison we measured lap shear strengths for two adhesives (EA2 and H2071) on cleaned, cold rolled steel of a comparable thickness (see Table II).

For EA2 the highest initial lap shear strength for the galvanized substrates is for electroplated (15,000 kPa). As shown in Table III, on the other hand, for cleaned steel of the same thickness, we found a mean strength of 11,200 kPa, some 35% less than the value for electroplated. Furthermore, since this difference is significant with respect to the recorded standard deviations, for this adhesive its adhesion to electroplated galvanized is somewhat "better" than to cold-rolled steel. No such difference is apparent for H2071, however, but it must be remembered that prior to environmental exposure, lap shear samples of H2071 on the galvanized substrates always failed cohesionally, *i.e.*, within the adhesive itself.

A comparison of strength retention after water immersion and six-week scab corrosion environments can be made from data listed

TABLE III
Lap shear strengths (kPa): Miscellaneous substrates

Adhesive	Substrate/thickness (mm)	Shear strength/standard deviation			
		Initial	7 day, 60°C H_2O	3 week scab	6 week scab
EA2	Cleaned Steel/0.94	11200/1000	—	—	—
EA2	Cleaned Steel/2.36	24400/300	—	19300/700	15000/1900
EA2	Oiled Steel/2.36	24200/300	—	19100/800	17900/900
H2071	Cleaned Steel/0.94	7600/700	—	—	—
H5188	Cleaned Steel/2.36	32700/1800	27700/1500	—	—
H1989	Cleaned Steel/2.36	38000/2000	29600/1300	33500/1400	30700/800
H1989	Cleaned Zincrometal/1.02	12400/400	13400/600	12400/1000	13000/400

TABLE IV
Comparative strength retention values (%): Miscellaneous substrates

Adhesive	Substrate/thickness (mm)	Strength retention/standard deviation		
		7 day, 60°C H_2O	3 week scab	6 week scab
EA2	Cleaned Steel/2.7	—	81/6	63/9
EA2	Oiled Steel/2.7	—	79/3	74/5
H5188	Cleaned Steel/2.7	85/7	—	—
H1989	Cleaned Steel/2.7	78/5	88/6	81/5
H1989	Cleaned Zincrometal	100/6	100/9	104/4

in Tables III and IV for the standard thick (2.7 mm) cleaned steel samples. Data for the three adhesives EA2, H5188, and H1989 on this standard substrate were obtained. As far as strength retention after both environments, the highest values for a galvanized substrate (electroplated: range 66–82%) still fall below that for cleaned steel (range 78–88%). Recorded standard deviations indicate that this conclusion is marginally significant, since in each case the ranges about the mean value for retention overlap. For H5188 and H1989, there is no significant difference between the highest values for galvanized (electroplated in the case of H5188, minimum spangled for H1989) and the values for cleaned steel.

Finally, results for H1989 on substrates which were treated with a zinc-rich paint ("zincrometal") prior to bonding suggest that although the highest initial strength of any substrate (22,000 kPa on electroplated galvanized) is 85% greater than that on zincrometal, the zincrometal/adhesive bond is exceptionally durable (100% retention in both environments). These results are not unexpected, since the lower strength for zincrometal reflects failure of the primer, rather than of the adhesive or adhesive/primer interface. The high durability is in part a result of the chemical compatibility of the zincrometal and the particular adhesive. It has been shown previously,[2] that very low interfacial energies (and consequently high environmental stability) result from this type of interface, provided no primer degradation occurs in the bonding process.

SUMMARY AND CONCLUSIONS

We have conducted a detailed comparison of lap shear data for initial strengths, seven-day (60°C) water immersion, and scab-corrosion-accelerated environmental exposures of five different epoxy adhesives, including three two-part and two one-part systems (all but one are currently commercially available), bonded to three different types of cleaned and oiled galvanized steel substrates (two "hot-dipped", one "electroplated"). The following conclusions have been drawn on the basis of this work.

1) In general, relative adhesion as measured by lap shear strength, is specific to the galvanized substrate type. For example,

we have found that for a given adhesive/substrate system, adhesion to "hot-dipped" (*i.e.* ultrasmooth and minimum spangled) galvanized substrates is harder to achieve and to maintain under accelerated environmental exposure than is adhesion to electroplated galvanized.

2) For a given type of galvanized substrate, the one-part epoxies evaluated generally give better strengths and strength retention than do two-part epoxies. One commercially available two-part did, however, show rough equivalence to the one-parts in most of those cases where a direct comparison could be made.

3) For a given adhesive on a particular type of galvanized steel, cleaned (solvent-wiped) and oiled (mineral seal oil) substrates show no significant differences in strength or durability.

In a second paper,[1] substrate chemistry, morphology, and bond failure surfaces have been analyzed to provide insights into the factors which contribute to these conclusions.

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