Joining Technologies: **High Strength Steel Weldability DOE Test Method Correlation**
(December 2, 1998)

1.0 Background And Executive Summary

In 1994, the Auto/Steel Partnership's Welding Task Force completed development of standard test methods to assess the resistance spot weldability of automotive sheet steels. The Welding Task Force published these standards in its Weld Quality Test Method Manual(1) in early 1995. The objective of developing standard test methods was to eliminate the need for repeat testing of a material with three different test methods (Chrysler's, Ford's, and GM's) to qualify a sheet steel grade. However, to obtain acceptance of the A/SP test methods as industry-wide standards, a correlation study was initiated to evaluate the A/SP Weld Quality Endurance Test (WQET) by comparing it against the existing Chrysler, Ford, and General Motors test methods presently used for welding qualification testing of coated automotive sheet steels. Three coated sheet steel materials (hot-dip galvanized, electrogalvanized, and galvannealed), and two welding machines (pedestal and C-frame) were used in this study. All welding was performed at Candid Logic Incorporated.

Statistical analyses of the endurance test data obtained with the Chrysler and A/SP test methods show that there are no significant differences between their means except for the hot-dip galvanized material welded on the C-frame machine. The analysis-of-variance test (ANOVA) performed on the Chrysler and all A/SP (both machines) data indicates that test method does not significantly affect endurance limits. Statistical analyses of the endurance test data obtained with the Ford and A/SP test methods show that there are significant differences between their means when each test's termination criteria are used to determine the endurance limit. However, when Ford-comparable termination criteria are used to determine the endurance limits of the A/SP data, no statistically significant differences between the Ford and A/SP data are noted for the HDG and EG materials, but significant differences still exist for the galvannealed material. One explanation for this difference is the unusually short (1750 and 2250 welds) electrode life results for the galvannealed material with the Ford test/criteria.

ANOVA results for the A/SP current range data (both machines) show that current range is strongly affected by the point at which current range was determined – before the endurance test (initial) or after the endurance test (final) using the enlarged electrodes. The composite means for all materials are 1.10 kA for ICR (initial) and 1.88 kA for FCR.(final). Coating type (material factor) also affects current range and the interactions with other factors. The machine factor showed no significance in this ANOVA. The ANOVA results for the A/SP test data (C-frame machine) and the GM current range data again show that test type (initial, final, or GM) is significant but that material (coating type) has a more significant effect in this data group. The analysis indicates that the differences or similarities between the A/SP and GM current ranges are material dependent. Also, the A/SP final and GM current ranges show significantly more scatter in results than the A/SP initial current ranges. This behavior is probably related to the enlarged electrode faces, their condition at the end of the endurance test of A/SP final current range tests, or the larger electrode faces used in the GM tests.

2.1 Materials

Three types of coated sheet steels – hot-dip galvanized, electrogalvanized, and galvannealed – were used in this study. They were supplied by three A/SP steel companies free of charge. Table 1 lists the materials' codes, thicknesses, and coating data (where available). Table 2 shows the substrate compositions (where available).

TABLE 1. Material And Coating Data

Coil Code*	Sheet Thickness (mm)	Substrate Type	Coating Type*	Coating Composition & Weight Al	Fe	Pb	Side 1 (g/m²)	Side 2 (g/m²)
HDG	0.77	IF	HDG	0.32	0.55	<0.02	87.9	81.7
EG	0.77	DQSK	EG	NA*	NA	NA	NA	NA
GA	0.74	DQSK	GA	NA	NA	NA	NA	NA

Note: * HDG = hot-dip galvanized, EG = electrogalvanized, GA = galvannealed, NA = Not Available

TABLE 2. Substrate Composition

Coil Code	Composition (weight %) C	Mn	P	S	Si	Al	Cu	Ni	Cr	Nb	Ti	N
HDG	0.003	0.14	0.012	0.010	0.005	0.040	0.012	0.022	0.032	<0.005	0.056	0.0030
EG	Not Available											
GA	Not Available											

2.2 Equipment

Two types of welding machines were used – a pedestal welder (used for Ford tests) and a C-frame fixture (used for Chrysler and GM tests). Both machines are currently used for qualification testing by the respective auto companies. The pedestal machine was used for comparing the A/SP WQET test to the Ford test while the C-frame fixture was used to compare the WQET test to the Chrysler test and the GM tests. No information about machine properties, such as cylinder size and type, capacity, etc., was supplied by Candid Logic for this report.

2.3 Test Methods and Welding Parameters

The test methods and their specified welding parameters are listed in Table 3. To provide an overview of how each test method assesses spot weldability, a brief description of which criteria are used follows.

1. The A/SP WQET test assesses spot weldability of coated sheet steel by:
   a) determining initial minimum and maximum current levels (II_{MIN} and II_{MAX})
   b) determining the operating current for the endurance test
   c) determining the number of welds achievable before all test welds at a sampling point fail to meet the minimum button size (Weld Quality Endurance Test)
   d) determining final minimum and maximum current levels (FI_{MIN} and FI_{MAX})
   e) calculating initial and final current ranges (I_{CR} and F_{CR})
2. The Chrysler and Ford tests assess spot weldability of coated sheet steel by:
   a) determining the operating current for the endurance test
   b) determining the number of welds achievable before test welds fail to meet the minimum button size and end of test criteria (endurance test)
3. The GM test assesses spot weldability of coated sheet steel by:
   a) determining I_{MIN} and I_{MAX} current levels for four weld times
   b) calculating the current ranges for each weld time and determining if the current range and current level weld lobe data meet the requirements

To obtain copies of the test specifications(1, 2, 3, 4), contact A/SP offices or the respective auto companies.TABLE.

TABLE 3. Test Methods and Welding Parameters

Company	Test* Specification	Electrode Face Dia. (mm)			Weld Time (cy)			Squeeze Time (cy)	Hold Time (cy)	Force (lbF)			Welding Rate (welds/min)
		HD	EG	GA	HD	EG	GA	All	All	HD	EG	GA	All
A/SP	WQET(1)	5.0	5.0	5.0	11	11	11	60	5	450	450	450	25
Chrysler	LP-461K-170(2)	5.1	5.1	4.8	7	7	6	24	5	525	525	400	60
Ford	BA-113-1(3)	6.4	6.4	6.4	12	12	12	60	5	500	500	500	25
GM	MDS-247(4)	6.4	6.4	6.4	13	13	13	60	2	500	500	500	NA

Note: * Numbers in parentheses are reference numbers

2.4 Experimental Design

Because of funding and time constraints, the study was designed to obtain the maximum amount of necessary data with the minimum number of tests. Instead of using an array where all materials are run with all test methods and both machines, the array was set up as shown in Table 4. Duplicate tests were run with each combination. With the pedestal machine, only the Ford and A/SP test methods were run. No Chrysler and GM tests were run on the pedestal welder. With the C-frame welder, the A/SP, Chrysler, and GM test methods were run. No Ford tests were run on the C-fixture. Because of this design, the statistical analyses were blocked by machine except for the A/SP test, which was run with both machines, allowing for a machine comparison to be made. Analysis-of-variance (ANOVA) and means comparison tests were performed as appropriate.

TABLE 4. Test Matrix for Test Method Correlation Study

Material Code	Pedestal Machine		C-Frame Fixture		
	A/SP WQET	Ford BA-113-1	A/SP WQET	Chrysler LP-461K-170	GM MDS-247
HDG	2X	2X	2X	2X	2X
EG	2X	2X	2X	2X	2X
GA	2X	2X	2X	2X	2X

Note: X = number of tests per procedure

3.1 Hot-Dip Galvanized Material

Table 5 shows the data for the hot-dip galvanized material. Electrode life and current range data obtained with the A/SP test and the pedestal welder (TW) are typical for this material. The Ford test with this material/welder combination appears to yield shorter electrode lives (1625 welds) than the A/SP test (2700 welds), but this difference is primarily a result of the more stringent Ford criteria. When the A/SP data are analyzed using the Ford criteria and a minimum button diameter that is comparable to a Ford minimum for this electrode size (5.0 - 0.8 = 4.2), the mean (1300 welds) is lower than but similar to the Ford mean (1625 welds). The A/SP test's electrode life results with the C-frame (CF) machine (1300 welds) are, however, significantly lower than those with the pedestal welder (2700 welds) and those obtained with the Chrysler test (2325 welds). No reasonable explanation exists for this behavior because the other materials did not exhibit this behavior.

Table 5. Data For Tests With The Hot-dip Galvanized Material

Test Code (Test Type-Material-Machine-Test No.)	Face Dia. (mm)	Min. Dia. (mm)	II_{MIN} (kA)	II_{MAX} (kA)	II_{CR} (kA)	I_{OP} (kA)	No. of Welds to Min. Dia.	FI_{MIN} (kA)	FI_{MAX} (kA)	FI_{CR} (kA)
A/SP-HD-TW-1(a)	5.0	3.5	8.56	9.61	1.05	9.52	2400	11.0	11.9	0.9
A/SP-HD-TW-2(a)	5.0	3.5	8.76	9.63	0.87	9.48	3000	10.7	12.4	1.7
Mean(a)			*8.66*	*9.62*	*0.96*	*9.50*	*2700*	*10.8*	*12.1*	*1.3*
A/SP-HD-TW-1(b)	5.0	4.2					1000			
A/SP-HD-TW-2(b)	5.0	4.2					1600			
Mean(b)							1300			
Ford-HD-TW-1	6.4	5.6	–	–	–	13.5	1750	–	–	–
Ford-HD-TW-2	6.4	5.6	–	–	–	13.5	1500	–	–	–
Mean						*13.5*	*1625*			
A/SP-HD-CF-1	5.0	3.5	8.39	9.44	1.05	9.46	1400	10.1	11.2	1.1
A/SP-HD-CF-2	5.0	3.5	8.37	9.46	1.09	9.26	1200	9.6	11.1	1.5
Mean			*8.38*	*9.45*	*1.07*	*9.36*	*1300*	*9.85*	*11.15*	*1.3*
Chrysler-HD-CF-1	5.1	3.6	–	–	–	11.0	2374	–	–	–
Chrysler-HD-CF-2	5.1	3.6	–	–	–	11.0	2274	–	–	–
Mean						*11.0*	*2324*			
GM-HD-CF-1	6.4	4.0	12.1	14.1	2.0	–	–	–	–	–
GM-HD-CF-2	6.4	4.0	11.9	13.7	1.8	–	–	–	–	–
Mean			*12.0*	*13.9*	*1.9*					

Note: (a) A/SP-HD-TW tests to A/SP minimum (3.5 mm)
(b) Same A/SP-HD-TW tests to comparable Ford minimum (4.2 mm for a 5 mm electrode face) for electrode life

The current range data for the A/SP test are typical for this material and show no differences between machines. The final current ranges (FICR) are wider than the initial current ranges (IICR) for both machines, a behavior that is consistent in the A/SP test because the electrode-face diameter is larger at the end of the endurance test, the point at which the final current levels are determined. The GM current ranges are also wider than the A/SP current ranges with the CF machine because the GM test specifies larger electrodes.

3.2 Electrogalvanized Material

The data for the electrogalvanized material, shown in Table 6, reveal a significant difference between the A/SP (TW machine) and Ford data when the A/SP minimum button diameter is used, but virtually no difference is noted when the Ford-comparable minimum (4.2 mm) is used. Interestingly, the means for the Ford test and Ford criteria for the electrogalvanized (1875 welds) and the hot-dip galvanized (1625 welds) materials are similar and fall below Ford’s 2000 weld minimum. Electrode life results for the C-frame (CF) machine and the A/SP test are only slightly lower than with the pedestal welder. The A/SP-CF endurance test results are similar to those obtained with the Chrysler test. The EG current range results are similar to the HDG material except that the A/SP final current ranges are wider and the GM current ranges are considerably narrower for the EG material. The means of the A/SP IICR data (both machines) is virtually identical to the mean of the GM data.

Table 6. Data For Tests With The Electrogalvanized Material

Test Code (Test Type-Material-Machine-Test No.)	Face Dia. (mm)	Min. Dia. (mm)	II_{MIN} (kA)	II_{MAX} (kA)	II_{CR} (kA)	I_{OP} (kA)	No. of Welds to Min. Dia.	FI_{MIN} (kA)	FI_{MAX} (kA)	FI_{CR} (kA)
A/SP-EG-TW-1(a)	5.0	3.5	8.96	9.90	0.94	9.78	5200	10.6	12.8	2.2
A/SP-EG-TW-2(a)	5.0	3.5	9.30	10.2	0.90	10.0	4800	10.8	12.8	2.0
Mean(a)			*9.13*	*10.05*	*0.92*	*9.89*	*5000*	*10.7*	*12.8*	*2.1*
A/SP-EG-TW-1(b)	5.0	4.2					1200			
A/SP-EG-TW-2(b)	5.0	4.2					1800			
Mean(b)							1500			
Ford-EG-TW-1	6.4	5.6	–	–	–	13.2	1750	–	–	–
Ford-EG-TW-2	6.4	5.6	–	–	–	13.3	2000	–	–	–
Mean						*13.25*	*1875*			
A/SP-EG-CF-1	5.0	3.5	8.17	9.02	0.85	8.78	4200	9.2	11.1	1.9
A/SP-EG-CF-2	5.0	3.5	8.07	9.18	1.11	9.00	5000	10.0	11.6	1.6
Mean			*8.12*	*9.10*	*0.98*	*8.89*	*4600*	*9.6*	*11.35*	*1.75*
Chrysler-EG-CF-1	5.1	3.6	–	–	–	10.5	4749	–	–	–
Chrysler-EG-CF-2	5.1	3.6	–	–	–	10.3	5274	–	–	–
Mean						*10.4*	*5012*			
GM-EG-CF-1	6.4	4.0	11.9	12.5	0.6	–	–	–	–	–
GM-EG-CF-2	6.4	4.0	11.3	12.7	1.4	–	–	–	–	–
Mean			*11.6*	*12.6*	*1.0*					

Note: (a) A/SP-EG-TW tests to A/SP minimum (3.5 mm)
(b) Same A/SP-EG-TW tests to comparable Ford minimum (4.2 mm for a 5 mm electrode face) for electrode life

3.3 Galvannealed Material

The data for the galvannealed material, shown in Table 8, reveal significant differences between the A/SP (TW machine) data (for both the A/SP and the Ford-comparable electrode life criteria of the A/SP data) and the Ford data. This behavior appears to show that significant differences in electrode life could be expected between the A/SP test and the Ford test when testing a material that exhibits slow electrode wear, such as galvannealed. The Ford results for the galvanneal material are quite low (2000 welds) for this coating type and are not significantly different from the HDG (1625 welds) and EG (1875 welds) results. These results appear to

Table 8. Data For Tests With The Galvannealed Material

Test Code (Test Type-Material-Machine-Test No.)	Face Dia. (mm)	Min. Dia. (mm)	II_{MIN} (kA)	II_{MAX} (kA)	II_{CR} (kA)	I_{OP} (kA)	No. of Welds to Min. Dia.	FI_{MIN} (kA)	FI_{MAX} (kA)	FI_{CR} (kA)
A/SP-GA-TW-1(a)	5.0	3.5	8.22	9.05	0.83	8.87	5800	10.9	13.0	2.1
A/SP-GA-TW-2(a)	5.0	3.5	8.37	9.21	0.84	9.07	6800	12.1	13.8	1.7
Mean(a)			*8.30*	*9.13*	*0.83*	*8.97*	*6300*	*11.5*	*13.4*	*1.9*
A/SP-GA-TW-1(b)	5.0	4.2					4600			
A/SP-GA-TW-2(b)	5.0	4.2					6400			
Mean(b)							5500			
Ford-GA-TW-1	6.4	5.6	–	–	–	13.2	1750	–	–	–
Ford-GA-TW-2	6.4	5.6	–	–	–	13.0	2250	–	–	–
Mean						*13.1*	*2000*			
A/SP-GA-CF-1	5.0	3.5	7.47	8.72	1.25	8.50	6400	11.1	13.5	2.4
A/SP-GA-CF-2	5.0	3.5	7.32	8.60	1.28	8.40	6000	9.7	13.2	3.5
Mean			*7.40*	*8.66*	*1.26*	*8.45*	*6200*	*10.4*	*13.35*	*2.95*
Chrysler-GA-CF-1	4.8	3.1	–	–	–	9.04	5774	–	–	–
Chrysler-GA-CF-2	4.8	3.1	–	–	–	9.00	6124	–	–	–
Mean						*9.02*	*5949*			
GM-GA-CF-1	6.4	4.0	11.4	13.8	2.4	–	–	–	–	–
GM-GA-CF-2	6.4	4.0	11.1	13.8	2.7	–	–	–	–	–
Mean			*11.25*	*13.8*	*2.55*					

Note: (a) A/SP-GA-TW tests to A/SP minimum (3.5 mm)
(b) Same A/SP-GA-TW tests to comparable Ford minimum (4.2 mm for a 5 mm electrode face) for electrode life

show that the Ford test does not discriminate well between a coating that is known to produce long electrode life (galvannealed) and one that typically produces much shorter electrode life (hot-dip galvanized).

The electrode life results with the C-frame (CF) machine and the A/SP test are slightly lower than with the pedestal welder. The A/SP-CF endurance test results for this material are similar to those obtained with the Chrysler test. The means for both machines' A/SP initial current ranges are lower than those for the GM test and the A/SP final current ranges. The means for the A/SP final current ranges with the pedestal welder are slightly lower than the mean of the GM current ranges while the means for the A/SP final current ranges with the CF welder are higher.

4.1 Material and Machine Effect On Electrode Life For The A/SP-WQET Test

The analysis-of-variance (ANOVA) results (Table 9) for all A/SP-WQET endurance test data indicates that only material has a significant effect on electrode life. No significance is noted for the machine factor and the machine/material

TABLE 9. Results Of ANOVA Test For A/SP Electrode Life Data

Variable	ANOVA F Ratio	$F_{0.95}$ Critical	Prob>F	R^2
Whole Model	**14.63**	4.39	**0.0026**	0.92
Material	**34.38**	5.14	**0.0005**	-
Machine	0.41	5.99	0.5470	-
Material X Machine	2.01	5.14	0.2033	-

Note: The areas in bold show statistical significance at the 95% confidence level.

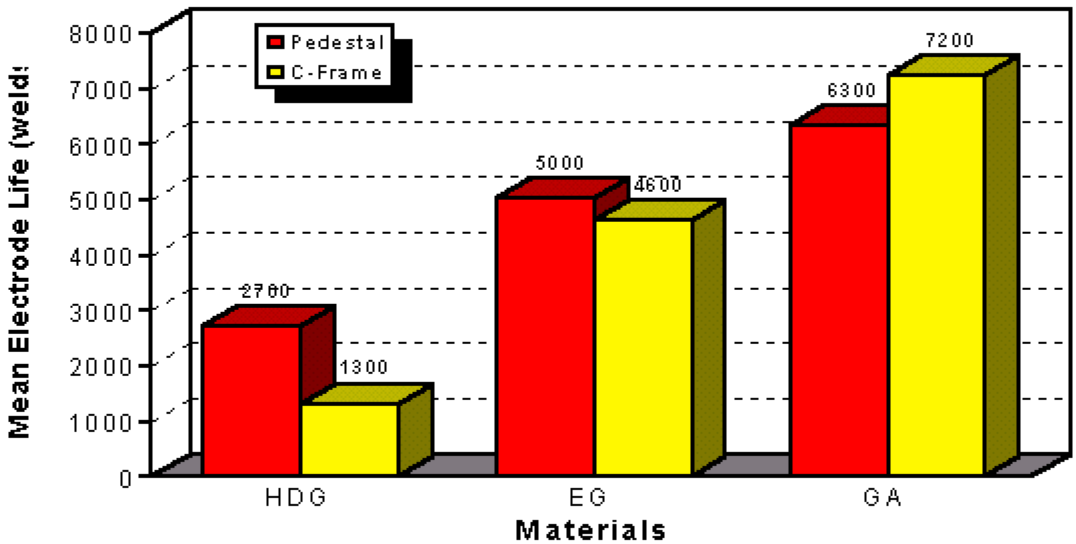

Figure 1. Mean Electrode Life Data For All A/SP WQET Tests

interaction. Figure 1 plots the means for all A/SP-WQET data (both machines and all three materials). Considering the type of coatings (HDG, EG, and GA) used in this study and the wide range of electrode life they typify, it is not surprising that the material (coating) factor appears to show high significance in the ANOVA. Although the machine factor shows no significance in the ANOVA, it is apparent from Figure 2 that the mean of the hot-dip galvanized material with the C-frame machine (1300 welds) is significantly lower than the mean with the pedestal welder (2700 welds). However, in the ANOVA, this difference is negated by the galvannealed material having longer electrode lives with the C-frame machine.

4.2 Material and Machine Effect On Current Range For The A/SP-WQET Test

The ANOVA that was performed to determine the effect of machine, material, and test (initial or final) factors and their interactions on current range for all A/SP-WQET data indicates, as shown in Table 10, that the most significant effect on current range in these data is caused by "test" (initial or final). Figure 2, which plots the mean current ranges for all A/SP tests and materials, shows the means of the "initial" current ranges are consistently lower than those of the "final" current ranges, regardless of the machine used. Of the other two main factors (machine and material), material also has an effect on current range while machine does not. Of the interactions, the two that show significance are the interactions between material and test and between material and machine.

TABLE 10. Results Of ANOVA Test For A/SP Current Range Data

Variable	ANOVA F Ratio	$F_{0.95}$ Critical	Prob>F	R^2
Whole Model	**7.82**	2.72	**0.0006**	0.87
Test (Initial or Final CR)	**46.21**	4.75	**<0.0001**	-
Machine	2.81	4.75	0.1194	-
Material	**6.72**	3.89	**0.0110**	-
Test X Machine	0.02	4.75	0.8995	-
Test X Material	**6.07**	3.89	**0.0151**	-
Machine X Material	**4.30**	3.89	**0.0391**	-
Test X Machine X Material	1.40	3.89	0.2840	-

Note: The areas in bold show statistical significance at the 95% confidence level.

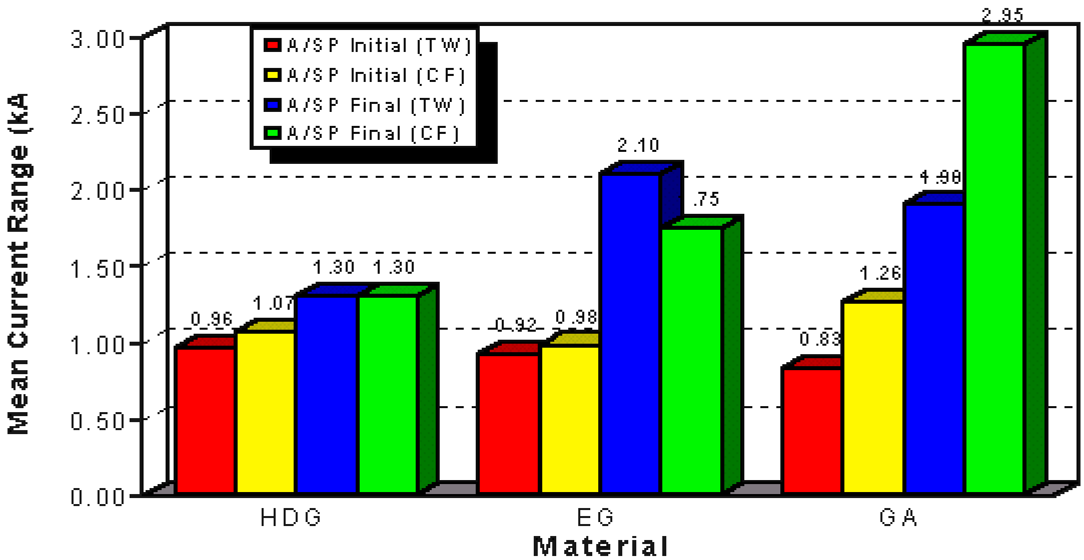

Figure 2. Current Range Means For All A/SP Tests.

The interpretation of this analysis is that there are significant differences between: a) initial and final current ranges of the A/SP test method, and b) materials (coating types). The difference between initial and final current ranges is primarily caused by the significantly larger electrode-face diameters that are inherent at the end of the endurance test, the point at which the final current range is determined. Larger face diameters generally result in wider current ranges.

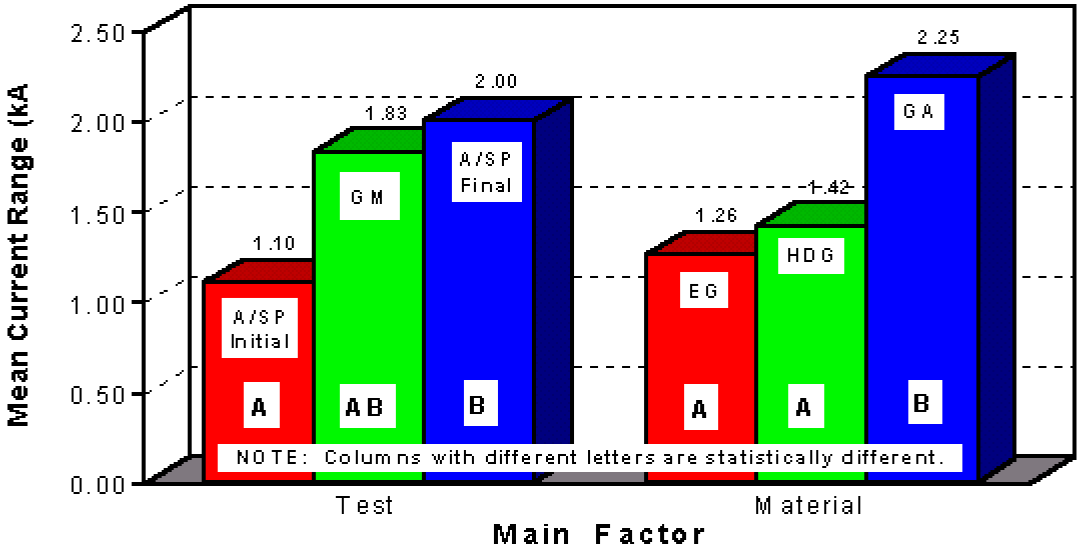

Figure 3. Current Range Means For Test And Material Categories.

Figure 4. Means Comparisons Of Current Ranges For A/SP-CF And GM Tests.

The ANOVA results, shown in Table 11, for these data indicate that both main factors (test and material) and their interaction have a significant effect on current range. Figure 4 shows the means for each test and each material. Means comparison tests (t-tests) reveal that the means between the A/SP-Initial (A) and A/SP-Final (B) current ranges are significantly different from each other, but neither is statistically different from the GM data (AB), as shown in Figure 4. Despite the large difference between the A/SP-Initial and GM means, the difference is not statistically significant because of the large variability between materials in the GM data. Figure 4 also shows that the mean of the GA (B) material is different from the means of the HDG (A) and EG (A) materials in the t-test means comparisons between materials.

TABLE 11. Results Of ANOVA Test For A/SP & GM Current Ranges

Variable	ANOVA F Ratio	$F_{0.95}$ Critical	Prob>F	R^2
Whole Model	**7.98**	3.23	**0.0023**	0.88
Test (A/SP-I, A/SP-F, or GM)	**11.38**	4.26	**0.0034**	-
Material	**14.30**	4.26	**0.0016**	-
Test X Material	**3.85**	3.63	**0.0431**	-

Note: The areas in bold show statistical significance at the 95% confidence level.

4.3 Correlation Between A/SP-WQET And Chrysler Endurance Test Data

The ANOVA results, listed in Table 12, for the A/SP C-Frame and Chrysler data indicate that only material has a significant effect on electrode life. Test method and the two factors' interaction have no significant effect. When the A/SP-TW data is included in the ANOVA, the analysis indicates again that material is the only factor that has an effect on electrode life. Test type and machine type have no significant effect. As Figure 5 shows, the pedestal welder (TW) produces slightly longer electrode lives, but this difference in means is primarily affected by the results for the HDG material with the C-Frame machine and A/SP test. These analyses show that the A/SP-WQET and Chrysler test methods produce similar results that can be correlated and incorporated into Chrysler's existing data base.

TABLE 12. ANOVA Results For A/SP & Chrysler Electrode Life Data

Data Group	Variable	ANOVA F Ratio	$F_{0.95}$ Critical	Prob>F	R^2
	Whole Model	**20.17**	4.39	**<0.0001**	0.89
A/SP CF and	Test (A/SP or Chrysler)	0.05	5.99	0.8221	-
Chrysler	**Material**	**40.70**	5.14	**<0.0001**	-
	Test X Material	0.86	5.14	0.4463	-
All A/SP (both	**Whole Model**	**24.39**	3.18	**<0.0001**	0.88
machines, CF and TW)	Test (A/SP or Chrysler)	0.02	4.67	0.8932	
and Chrysler	**Material**	**48.53**	3.81	**<0.0001**	
	Machine	0.45	4.67	0.5159	

Note: The areas in bold show statistical significance at the 95% confidence level.

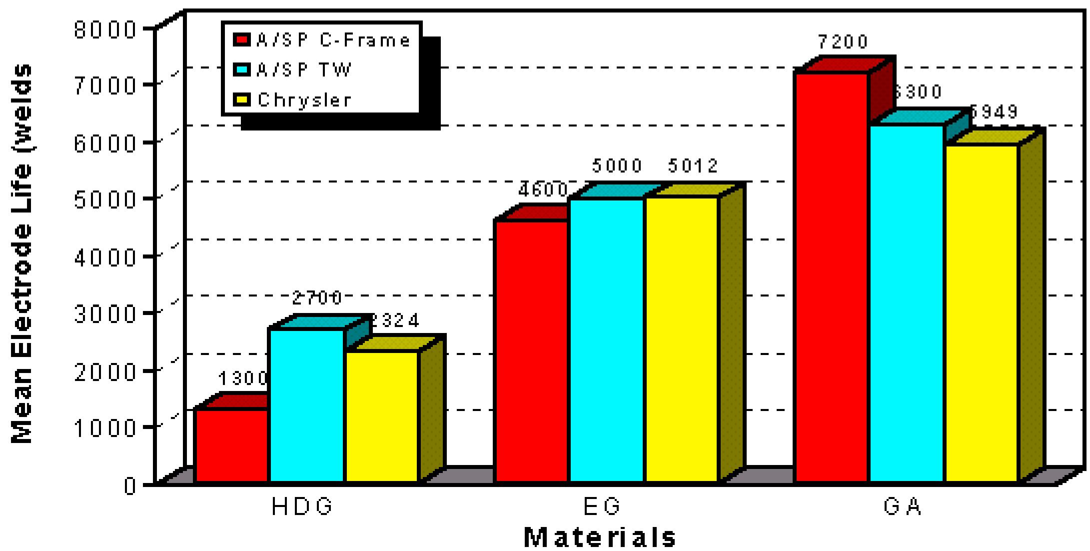

Figure 5. Mean Electrode Life Data For A/SP And Chrysler Tests.

4.4 Correlation Between A/SP-WQET And Ford Electrode Life Data

The ANOVA results, listed in Table 13, for the A/SP-TW data and the Ford data, using their respective end-of-life criteria, indicate that test has the most significant effect on electrode life. Material and the interaction between material and test are also significant. Figure 6 shows that there are sub-stantial differences between the means of the A/SP data and those of the Ford data when each test uses its own end-of-life criteria. The A/SP results are considerably longer primarily because of the smaller minimum button diameter specified by A/SP [3.5 mm for A/SP while a Ford-comparable mini-mum would be 4.2 mm (5 mm -0.8 mm)] and the A/SP requirement that all five peel test must fail at two consecutive checkpoints before test termination is reached. However, when the A/SP data are re-examined and the Ford-comparable test termination criteria (4.2 mm minimum button diameter, and no more than one of the five peel tests per checkpoint failing to meet that minimum) are applied, the results between the two tests come much closer for the HDG and EG materials, as Figure 6 shows. The data for the galvannealed material is the exception. When the Ford-comparable results for the A/SP tests are used with the Ford data, the ANOVA

TABLE 13. ANOVA Results For A/SP & Ford Electrode Life Data

Electrode Life Data Group	Variable	ANOVA F Ratio	$F_{0.95}$ Critical	Prob>F	R^2
A/SP-TW to A/SP	**Whole Model**	**47.52**	4.39	**<0.0001**	0.98
end-of-life (EOL) criteria and	**Test (A/SP or Ford)**	**152.51**	5.99	**<0.0001**	-
Ford to Ford	**Material**	**25.68**	5.14	**0.0011**	-
EOL criteria	**Test X Material**	**16.87**	5.14	**0.0034**	-
A/SP-TW to Ford-comparable	**Whole Model**	**13.96**	4.39	**0.0030**	0.92
EOL criteria and	**Test (A/SP or Ford)**	**7.23**	5.99	**0.0361**	
Ford to Ford	**Material**	**17.60**	5.14	**0.0031**	
EOL criteria	**Test X Material**	**13.68**	5.14	**0.0058**	

Note: The areas in bold show statistical significance at the 95% confidence level.

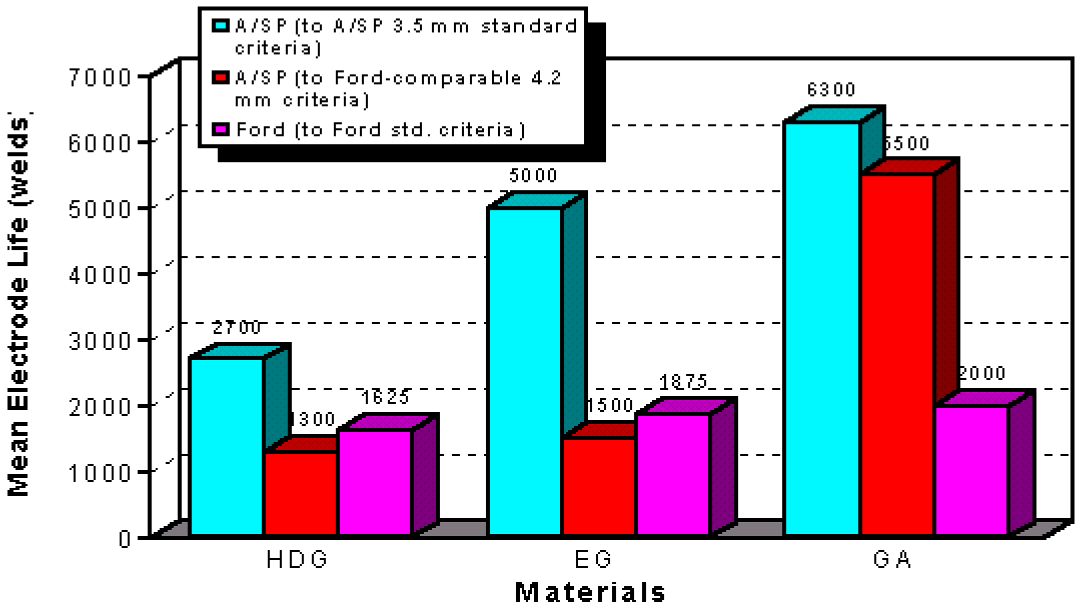

Figure 6. Mean Electrode Life Data For A/SP-TW And Ford Tests.

results still indicate that test type has an effect (because of the A/SP galvanneal data) but the F-ratio is considerably smaller than when the normal A/SP test termination criteria are used. This analysis thus suggests that the A/SP-WQET test method can be substituted for the Ford test with confidence that it will produce results that can be correlated to Ford's existing electrode life data base for EG and HDG steels when the Ford-comparable end-of-life criteria are used.

One notable observation regarding the Ford test is that it appears unable to differentiate clearly between materials of different electrode life properties. When examining the means of the Ford data for each of the three materials in Figure 6, it appears that the mean electrode lives for the three materials (HDG – 1625 welds, EG – 1875 welds, and GA – 2000 welds) are virtually identical. An ANOVA test on this data indicates no significance (F=1.17 for an F-critical of 9.55) of coating type on electrode life. It is well known that EG coatings generally produce considerably longer electrode lives than HDG coatings and that galvanneal coatings surpass electrode life performance of either of the other two. However, the data using the Ford method/criteria would indicate that their performances are very similar. Both of the tests with the HDG material, one test with the EG material, and one test with the galvannealed material do not even meet Ford's 2000 weld minimum. The A/SP test and the Chrysler test show good ability to discriminate between materials.

This correlation study to determine the ability of the A/SP test methods to produce results that can be correlated with existing automotive test methods reveals the following:

1. Statistical analyses of the A/SP endurance test data for all materials and both machines reveal that the A/SP

test is able to discriminate between the endurance performances of different coatings and that the two machines used in this study do not significantly affect the results.

2. Statistical analyses of A/SP current range data indicate that current range is strongly affected by the point at which current range is determined – before the endurance test (initial, with new electrodes) or after the endurance test (final, with the enlarged electrodes). That the final current ranges are somewhat to significantly wider than the initial current ranges and that the final current ranges exhibit considerably more scatter is probably caused by the enlarged and pitted electrode faces present at the end of the endurance test.

3. Statistical analyses of the A/SP and GM current range data indicate that test type [A/SP (initial & final) or GM] has a significant effect on current range. However, material (coating type) also appears to have a strong effect, and the interaction between test type and material shows significance. Also, the significantly higher scatter of the A/SP final and GM current ranges in comparison to the A/SP initial current ranges may be related to the enlarged electrode faces of the A/SP final test and the larger electrode faces specified in the GM test.

4. Statistical analyses of the A/SP and Chrysler endurance test data show that no statistically significant differences are apparent between the A/SP data and the Chrysler data and that both test methods can discriminate between the endurance performances of different coatings. These results suggest that the A/SP and Chrysler test methods produce similar results that could be correlated to and incorporated (if desired) into Chrysler's existing data base.

5. Statistical analyses of the Ford and A/SP data indicate that the Ford and A/SP test methods produce significantly different means when each test's termination criteria are used to determine the endurance limit. However, when Ford-comparable termination criteria are used to determine the endurance limits of the A/SP data, no statistically significant differences between the Ford and A/SP data are noted for the HDG and EG materials but significant differences are still evident for the galvanneal material. One explanation for this difference is the unusually short (1750 and 2250 welds) electrode life results for the galvannealed material with the Ford test/criteria.

1. Auto/Steel Partnership, "A/SP Weld Quality Test Method Manual," Rev. 0, 2/3/95.

2. Chrysler specification LP-461K-170, "Resistance Weldability Test For Bare, Galvanized, Galvannealed, High Strength, Low Carbon, And Interstitial-Free (IF) Hot And Cold Rolled Steel Sheet," Revision E, 3/31/92

3. Ford Motor Co. specification BA 113-1, "Welding Acceptance Test For Galvanized Low Carbon Steel."

4. General Motors Corp. specification MDS-247, "Specifications And Procedure For Determining The Weldability Of Body Steel Materials."