Spot Weldability of Mn-Mo-Cb, V-N, and SAE 1008 Steels

Compared to an SAE 1008 steel, the Mn-Mo-Cb and V-N high-strength low-alloy (HSLA) steels exhibit good weldability during automotive specification resistance spot-welding tests

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ABSTRACT. The basic spot-welding characteristics of two HSLA steels—Mn-Mo-Cb and V-N—were investigated and compared with those of an SAE 1008 carbon steel. Both the Mn-Mo-Cb steel and the V-N steel could be spot welded using the same electrode size, electrode force, and weld time as for the SAE 1008 steel of similar thickness. However, compared to the SAE 1008 steel, the welding current level was lower for the HSLA steels.

The spot weldability of the Mn-Mo-Cb steel was similar to that of the V-N steel with respect to the width and level of the welding current range and the tensile shear strength, but the cross-tension strength and "ductility ratio" of the Mn-Mo-Cb steel were higher than those of the V-N steel. Relationships between weld strength (in both tension and shear) and weld nugget size were established for all three steels. The type of fracture (interface vs. pullout) was explained in terms of the base-metal yield strength, sheet thickness, weld nugget size, and shear strength of the weld metal.

It was concluded that both HSLA steels exhibited good spot weldability. Compared to the SAE 1008 steel, the HSLA steels have a wider welding current range, higher tensile shear strength, and equivalent or higher cross-tension strength.

Introduction

The reduction of vehicle weight is one of the most important problems concerning the automobile industry. Over the last few years, HSLA steels have been considered as a possible substitute for low-carbon steel because of their higher strength-to-weight ratio. For automobile applications, HSLA steels are required to be spot weldable, since this form of resistance welding is a major process used for joining sheet-metal parts.

Good spot-welding practice requires that the following three parameters be controlled:

1. The welding current that passes through the joint to provide the heat.
2. The pressure between the electrodes that serves to keep the two or more sheet components in intimate contact.
3. The weld time during which the current is allowed to flow.

Other factors such as the clamping (hold) time after welding may also affect the weld ductility. In production, it is desirable to keep the welding parameters constant for different materials as much as possible; therefore, as HSLA steels become introduced, it is important to determine the necessity for adjusting process parameters during spot welding. In addition, it is essential that the mechanical properties of HSLA steel spot welds compare favorably with those of carbon steels.

In this work, the spot-welding characteristics of two HSLA sheet steels (Mn-Mo-Cb and V-N) having a minimum yield strength of 80 ksi (550 N/mm^2) and an SAE 1008 carbon steel were evaluated using a ductility test from an automotive company specification, tensile shear tests, and cross-tension tests. The ductility tests were performed by peeling spot welds and evaluating the type of failure and size of the weld button. In tensile shear and cross-tension tests, the effects of weld current and electrode force were studied.

Experimental Procedures

Materials

The materials used for this investigation were nominal 0.1 in. (2.5 mm) thick commercially produced as-hot-rolled Mn-Mo-Cb, V-N, and SAE 1008 steels in the pickled and oiled condition. The compositions, thicknesses,

Table 1—Chemical Compositions of Steels, %[a]

Steel designation	C	Mn	Si	Mo	Cb	V	Al	N	S	P	Ce
Mn-Mo-Cb	0.05	1.14	0.18	0.28	0.062	NA	0.050	0.009	0.011	0.004	0.018
V-N	0.09	1.06	0.27	NA	NA	0.09	0.018	0.028	0.010	0.008	0.038
SAE 1008	0.04	0.25	<.005	NA	NA	NA	0.022	0.002	0.032	0.011	NA

[a] NA = not analyzed.

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Table 2—Mechanical Properties and Thickness of Steel Sheets

Steel designation	Thickness of sheet, in. (mm)	Orientation[a]	0.2% offset yield strength, ksi (MPa)	Tensile strength, ksi (MPa)	Elongation, %	Reduction of area, %
Mn-Mo-Cb	0.098 (2.49)	L	80.5 (555)	86.6 (597)	24.8	64
		T	86.1 (593)	88.8 (612)	25.5	62
V-N	0.093 (2.36)	L	89.2 (615)	102.9 (709)	21.5	50
		T	95.6 (659)	106.2 (732)	19.0	53
SAE 1008	0.102 (2.59)	L	36.2 (249)	48.1 (331)	36.2	69
		T	35.8 (247)	46.5 (320)	38.9	70

[a] L = longitudinal; T = transverse.

Table 3—Welding Conditions

Welding parameter	Specific conditions for test specimens: Peel test	Tensile shear test	Cross-tension test
Squeeze time	45 cycles	45 cycles	45 cycles
Weld time	30 cycles	30 cycles	30 cycles
Hold time	30 cycles	30 cycles	30 cycles
Electrode force, lb (N)	1770 (7870)	1500 (6670) 1770 (7870) 2250 (10,010)	1500 (6670) 1770 (7870) 2250 (10,010)
Weld current	The current required to produce a pulled-out button diam. slightly larger than the electrode face diam. of 0.310 in. (7.87 mm) using 5-cycle hold time.	A current range extending 4-6 kA below minimum expulsion current	A current range extending 4-6 kA below minimum expulsion current
Electrode	¾ in. × 0.310 in. × 30 deg (19 mm × 7.87 mm × 30 deg)	¾ in. × 0.310 in. × 30 deg (19 mm × 7.87 mm × 30 deg)	¾ in. × 0.310 in. × 30 deg (19 mm × 7.87 mm × 30 deg)

and tensile properties of these steels are presented in Tables 1 and 2. The SAE 1008 steel had a carbon content (0.04%) that was low for this grade of steel, and the 1.14% Mn content of the Mn-Mo-Cb steel was also low for this grade.

Welding Conditions

The welding conditions were selected according to an automotive specification for resistance spot-weldability tests[1] although welding current and electrode force were varied above and below the recommended settings—Table 3.

Spot welding was performed on an AC air-operated welding unit having 100 kVA at 50% duty cycle. A Duffers current analyzer was used to measure the current of each weld.

The electrodes were a water-cooled conical Cr-Cu alloy (RWMA Class II) and were tapered from ¾ in. (19 mm) diameter to 0.310 in. (7.87 mm) diameter at an angle of 30 deg (included cone angle of 120 deg). They were conditioned at the start of welding and after completing all welds in one type of material (about 80 to 90 spot welds). Conditioning was performed by rotating a file lightly clamped between the electrodes and then making a series of practice welds.

Ductility (Peel) Test

Peel tests were performed according to a ductility test taken from an automotive specification.[1] The specimens consisted of two 6 by 4 in. (150 by 100 mm) coupons overlapped about 5 in. (125 mm) and joined by two spot welds—Fig. 1(a). During testing, the second weld was peeled apart as shown in Fig. 1(b), and the button diameter was measured with a caliper gauge.

Initially, the peel test was performed using the welding conditions shown in Table 3, with a shorter hold time of 5 cycles. The welding current was then adjusted to obtain a button diameter in the second weld equal to or slightly greater than the 0.310 in. (7.87 mm) electrode-cap face diameter. The hold time was then increased to 30 cycles without changing the other welding parameters, and two to four peel tests were performed in both longitudinal and transverse coupons.

Tensile Shear and Cross-Tension Tests

The strength of welds loaded parallel and normal to the interface was determined using the tensile shear test

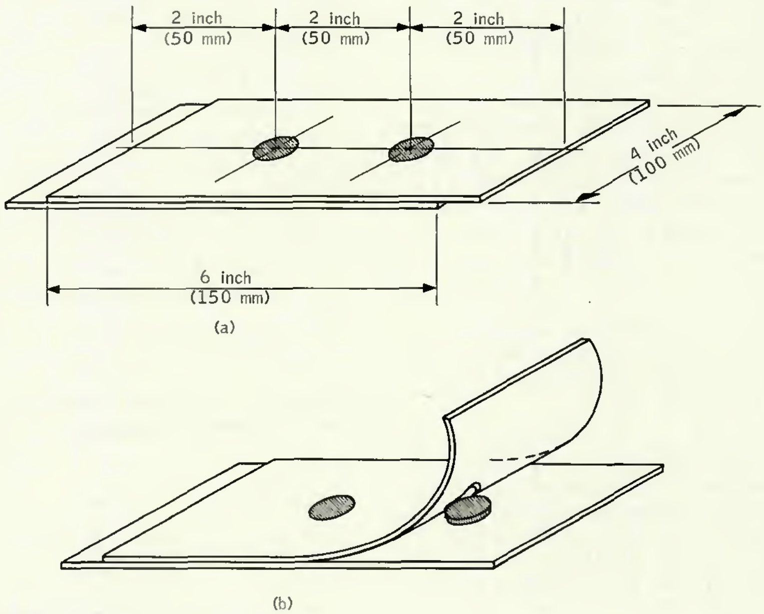


Fig. 1—Peel test

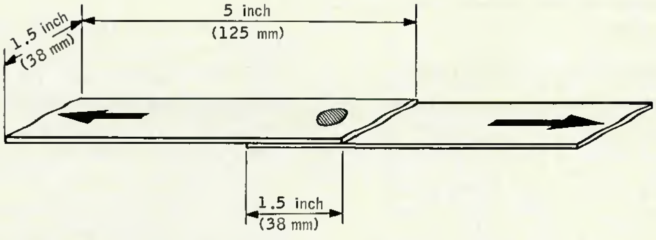


Fig. 2—Tensile shear specimen

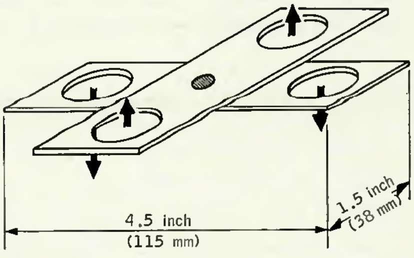


Fig. 3—Cross-tension specimen

and cross-tension test, respectively. In this paper, the spot-weld interface refers to the surface between the sheets before spot welding is performed.

The tensile shear specimen is shown in Fig. 2. The specimen was loaded in tension parallel to the weld interface until failure occurred. The cross-tension specimen is shown in Fig. 3. This specimen was loaded normal to the weld interface using a fixture designed for this test.

The cross-head speed was 2 ipm (50 mm/min) for both tests. The failure load, type of failure, and weld-button diameter were recorded for each test. Two types of failure are normally observed during testing of spot welds: pullout and interface failures. The root diameter was measured in welds that had exhibited pullout failure, using sharp-edge calipers, and the diameter of the weld-metal fracture surface was measured in welds that had failed along the spot-weld interface.

The weld-metal fracture surface was identified by its bright appearance. A surrounding halo having a gray appearance was observed in most interface failures but, upon sectioning the weld, the halo area was observed to be outside the fused region and, thus, was ignored when measuring the spot-

Table 4—Results of Ductility (Peel) Test

	Longitudinal			Transverse		
Material	Type of failure	Weld current, kA	Button diameter, in. (mm)	Type of failure	Weld current, kA	Button diameter, in. (mm)
Mn-Mo-Cb	Pull-out	13.0	0.30 (7.6)	Pull-out	13.2	0.32 (8.1)
	Pull-out	13.2	0.31 (7.9)	Pull-out	13.6	0.32 (8.1)
	Pull-out	13.2	0.32 (8.1)	Pull-out	14.0	0.34 (8.6)
				Pull-out	12.9	0.34 (8.6)
V-N	Pull-out	12.5	0.31 (7.9)	Pull-out	13.1	0.32 (8.1)
	Pull-out	13.0	0.31 (7.9)	Pull-out	12.1	0.32 (8.1)
				Pull-out	12.6	0.31 (7.9)
SAE 1008	Pull-out	17.2	0.32 (8.1)	Pull-out	17.3	0.32 (8.1)
	Pull-out	17.2	0.32 (8.1)	Pull-out	17.3	0.32 (8.1)
				Pull-out	17.1	0.29 (7.4)

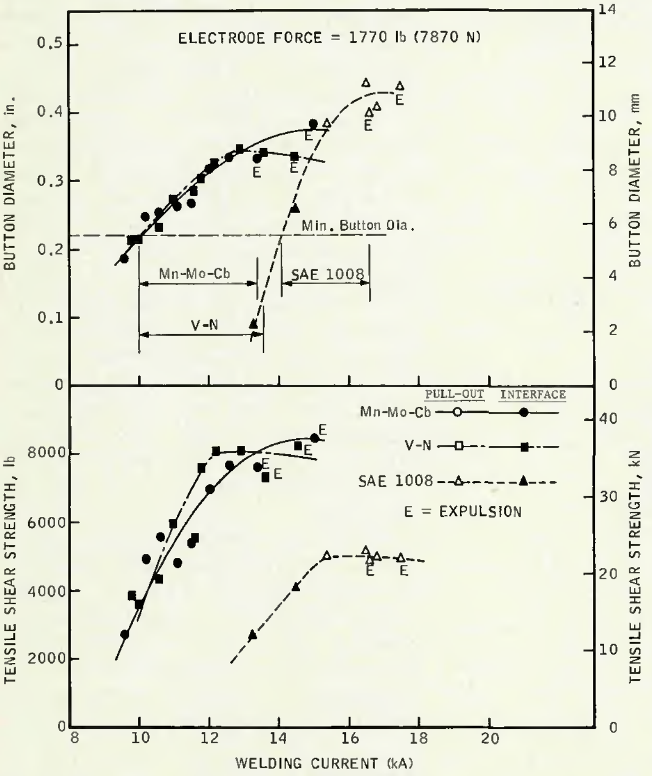


Fig. 4—Effect of welding current on the tensile shear strength and button diameter of spot welds; electrode force = 1770 lb (7870 N)

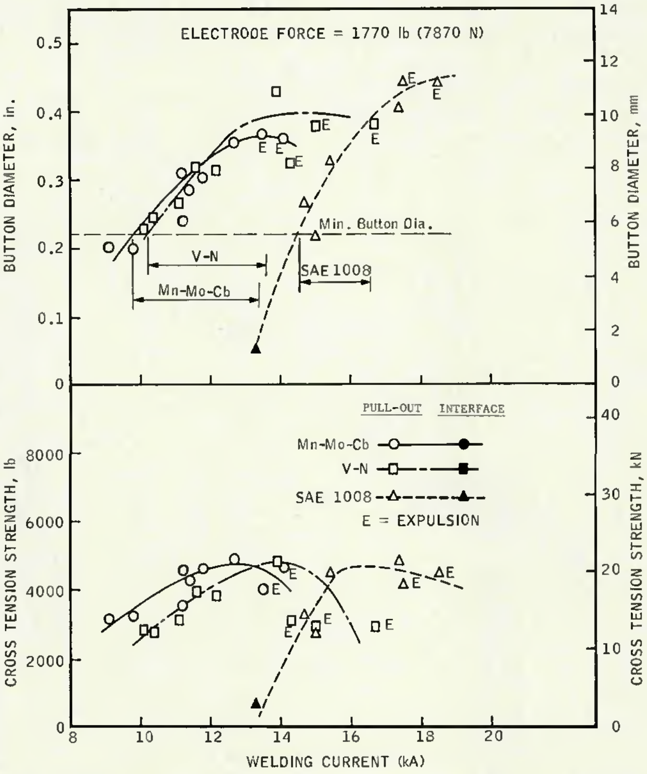


Fig. 5—Effect of welding current on the cross-tension strength and button diameter of spot welds; electrode force = 1770 lb (7870 N)

Table 5—Maximum Tensile Shear and Cross-Tension Strength

Material	Electrode force, lb (kN)	Maximum tensile shear strength, lb (kN)	Maximum cross-tension strength, lb (kN)
Mn-Mo-Cb	1500 (6.7)	8,600 (38.5)	5,200 (23.1)
	1770 (7.6)	8,500 (37.8)	4,800 (21.4)
	2250 (10.0)	8,100 (36.0)	5,000 (22.2)
V-N	1500 (6.7)	8,800 (39.1)	4,600 (20.5)
	1770 (7.6)	8,100 (36.0)	4,800 (21.4)
	2250 (10.0)	8,800 (39.1)	4,400 (19.6)
SAE 1008	1500 (6.7)	5,100 (22.7)	5,300 (23.6)
	1770 (7.6)	5,000 (22.2)	4,700 (20.9)
	2250 (10.0)	5,300 (23.6)	4,800 (21.4)

weld diameter.

Metallography and Hardness

Nine untested cross-tension specimens for each combination of the three materials and three electrode forces were mounted and examined. Microhardness tests were performed on selected samples using a diamond pyramid indenter and a 500 g load. In addition, hardness data of some tested cross-tension specimens of Mn-Mo-Cb steel were obtained to determine the failure mode.

Results and Discussion

Ductility (Peel) Test

Results of the ductility test are shown in Table 4. According to the specification,[1] "passing" requires that no sign of brittle fracture be observed at the weld interface or around the buttons. All the materials passed, since fully circular ductile pullout failure was obtained in all cases.

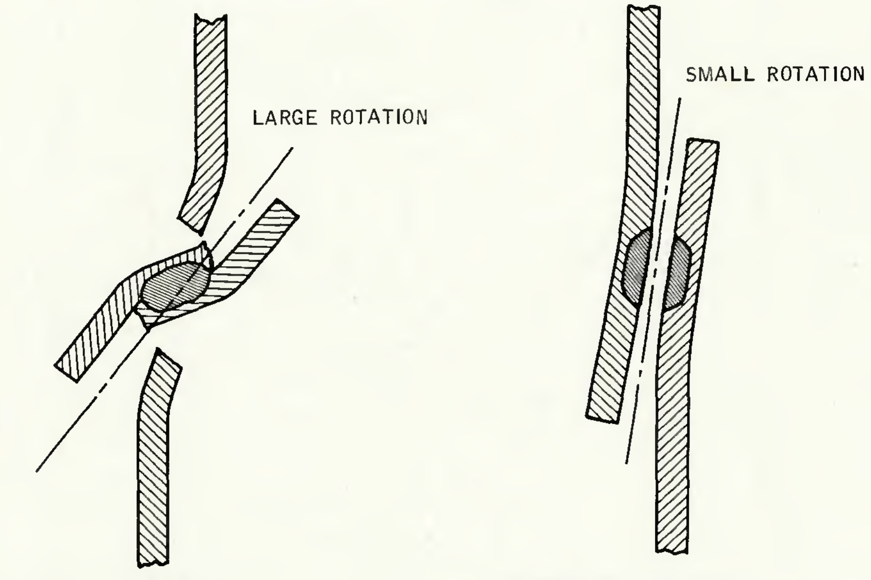
Tensile Shear and Cross-Tension Tests

The effects of welding current on the tensile shear strength and cross-tension strength are shown in Figs. 4 and 5 for an electrode force of 1770 lb (7870 N). Plots of weld-button diameter vs. welding current are also included. Both tensile shear strength and cross-tension strength increased rapidly with weld current at low current levels and reached a maximum at a higher current level with expulsion occurring at the higher currents.

Similar plots for these tests were obtained using an electrode force of 1500 and 2250 lb (6670 and 10,010 N), and the maximum strength obtained in both the tensile shear test and cross-tension tests is listed in Table 5. Electrode force had little effect on these values. Note also that the maximum tensile shear strength was higher for the two HSLA steels.

Types of Failure

Two types of failure are observed in spot-weldability tests: pullout failure and interface failure. In the former, failure occurs by ductile shearing through the thickness of the material so that a weld button is pulled out. In the second case, failure occurs along the weld interface. This latter failure tends to be considered brittle, although Pollard,[2] using a scanning electron microscope, observed ductile fracture in some interface fractures.



(a) PULL-OUT FAILURE (b) INTERFACE FAILURE

Fig. 6—Schematic diagram of failure types in tensile shear test

Interface failure occurred in most tensile shear tests of Mn-Mo-Cb steel and V-N steel while all cross-tension tests of these steels resulted in pullout failure. In the case of the tensile shear test, the type of failure depends on the combination of base-metal yield strength, sheet thickness, and shear strength of the weld metal.

During the test, the weld interface rotates so as to be more normal to the tensile direction, while at the same time the weld metal experiences shear loading. As the rotation proceeds, the stress normal to the weld interface increases very rapidly, but the shear stress increases at a decreasing rate. If the weld metal is strong enough to resist the shear stress, the weld-metal interface rotates sufficiently to cause pullout failure, as shown in Fig. 6(a); if not, interface failure takes place—Fig. 6(b).

With material having a higher yield strength or greater thickness, the rotation is smaller at the same load so that the shear stress increases much faster than for a lower strength or thinner material. Therefore, unless the shear strength of weld metal is extremely high, interface failure tends to occur. Because Pollard[2] reported pullout failures over a fairly wide range when testing a steel with 80 ksi (550 N/mm^2) yield strength and 0.075 in. (1.9 mm) thickness, this combination of strength and thickness seems to be critical.

The HSLA steels tested in this investigation had about the same strength level but about 30% greater thickness—Table 2. Although interface failure is not generally preferred, it should not be considered detrimental in this case, since both steels have tensile shear strengths that are higher than that of a conventional low-carbon steel, and both materials passed the ductility (peel) test.

In the cross-tension test, the load is normal to the spot-weld interface; therefore, pullout failure usually occurs unless the weld button is very small. A macrograph of a tested cross-tension specimen is presented in Fig. 7. This picture indicates that the fracture initiated at the weld bond.

Button Size vs. Strength

For both tensile shear and cross-tension tests, good correlation was

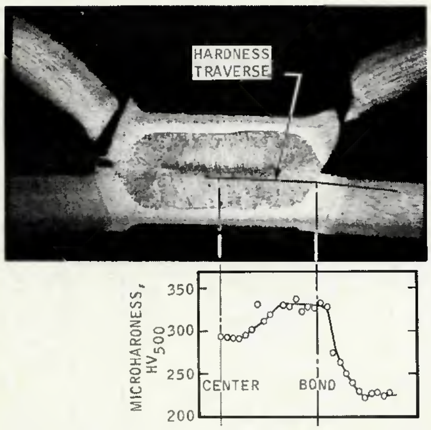


Fig. 7—Section through cross-tension specimens of Mn-Mo-Cb steel showing pullout failure and hardness profile. Aqueous saturated picric acid, ×7 (reduced 55% on reproduction)

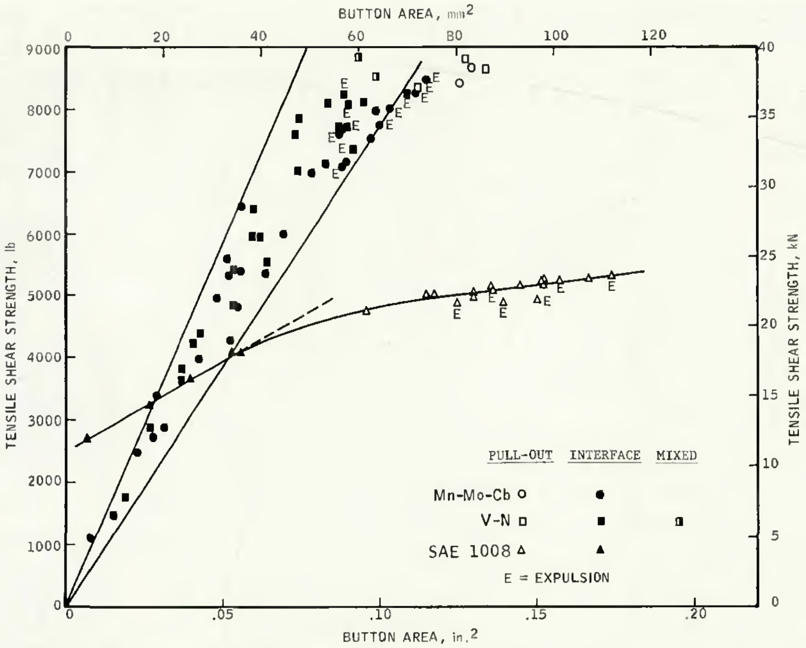


Fig. 8—Correlation between tensile shear strength and button area of spot welds

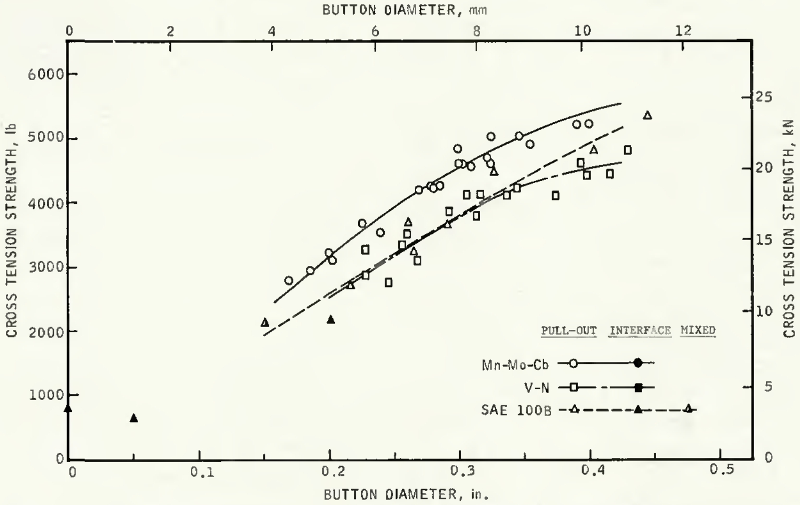


Fig. 9—Correlation between cross-tension strength and button diameter of spot welds

obtained between the button size and strength as shown in Figs. 8 and 9. The tensile shear strength increased linearly with weld-button area for interface failure, although it deviated from this correlation for pullout failure and expulsion (Fig. 8). The correlation for Mn-Mo-Cb and V-N steels fell within the same band, while that for SAE 1008 carbon steel had a different slope.

Cross-tension strength was plotted against button diameter rather than button area in Fig. 9. In pullout failure the strength is a function of nugget circumference (and thus diameter) rather than area. Spot welds that exhibited expulsion did not fit this correlation and were not plotted in Fig. 9. A second-order regression analysis of the data revealed the following relationship:

$$\text{Mn-Mo-Cb: } CTS = -28100\,D^2 + 27900\,D - 1270$$

$$\text{V-N: } CTS = -30000\,D^2 + 28100\,D - 1900$$

$$\text{SAE 1008: } CTS = -5000\,D^2 + 14600\,D - 120$$

where CTS = Cross Tension Strength (ksi) and D = Button Diameter (inches).

All three materials exhibited a similar trend, but the strength levels were somewhat different with the Mn-Mo-Cb steel exhibiting slightly higher cross-tension strength for a given button size.

Ductility Ratio

It is noteworthy that the cross-tension strength has little direct relationship to the base-metal strength. On the other hand, the tensile shear strength is dependent on base-metal strength. The cross-tension test applies more constraint to the weld region and is influenced by the ductility of the weld since, in this test, fracture initiates at the edge of the weld nugget as shown in Fig. 7.

A commonly used measure of spot-weld ductility is the ratio of the cross-tension strength to the tensile shear strength. This ratio is called the ductility ratio, and values of the ductility ratio are listed in Table 6 for a current level of 500 A below the expulsion current. Since the ductility ratio

Table 6—Ductility Ratio

		Ductility ratio	
Material	Electrode force, lb (kN)	For each electrode force	Average
Mn-Mo-Cb	1500 (6.7)	0.601	0.611
	1770 (7.6)	0.618	
	2250 (10.0)	0.615	
V-N	1500 (6.7)	0.525	0.528
	1770 (7.6)	0.557	
	2250 (10.0)	0.501	
SAE 1008	1500 (6.7)	0.925	0.906
	1770 (7.6)	0.898	
	2250 (10.0)	0.895	

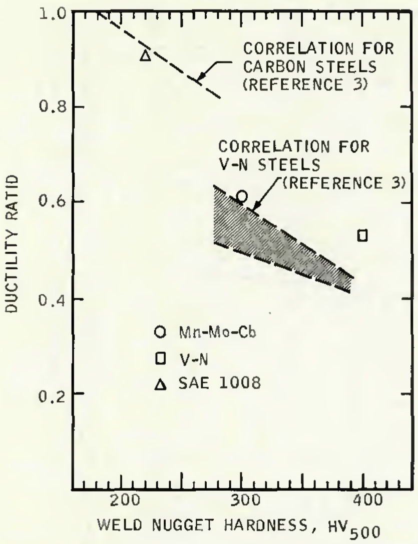


Fig. 10—Correlation between ductility ratio and weld-nugget hardness

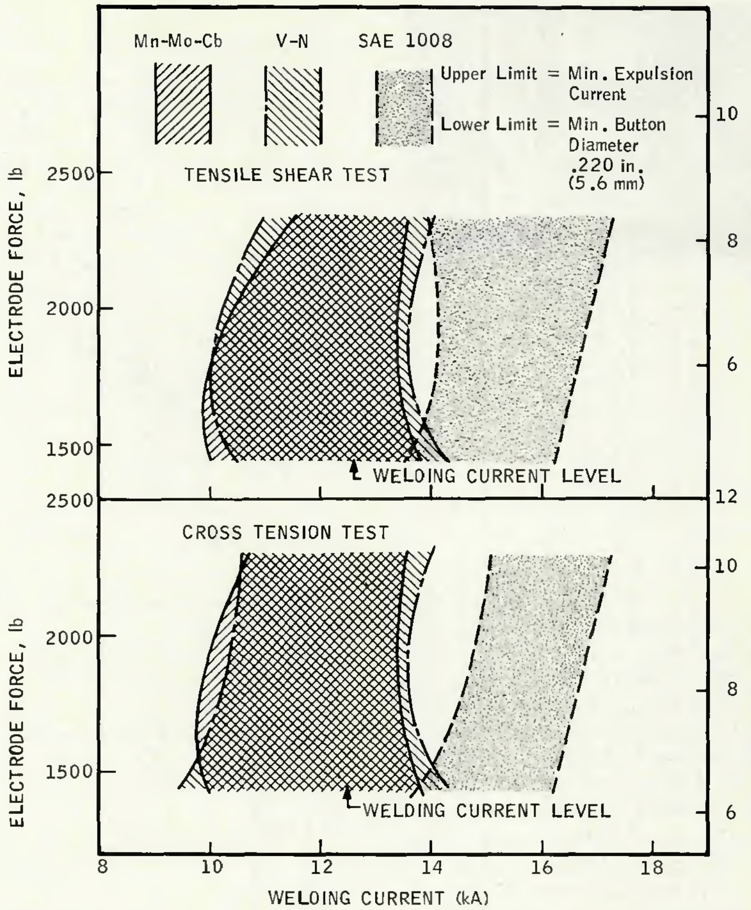


Fig. 11—Comparison of welding current ranges for HSLA steels and low-carbon steel

was similar for each electrode force used, an average ductility ratio was calculated for each material—Table 6. The ductility ratio is a measure of the anisotropy of the weld strength and indicates the number of additional spot welds required if designed loads are normal rather than parallel to the spot-weld interface.

The SAE 1008 steel exhibited a ductility ratio that was much higher than the two HSLA steels. The difference in ductility ratio between the two HSLA steels was smaller; however, the Mn-Mo-Cb steel exhibited a higher ductility ratio than the V-N steel.

The ductility ratio is a complex function of the weld ductility, base-metal strength, weld-metal and heat-affected zone strength, nugget size, and sheet-metal thickness. The ductility ratio of the three steels tested also seemed to fit the inverse correlation between ductility ratio and weld hardness that was determined by Pollard[3] and is plotted in Fig. 10.

In this work, the SAE 1008 carbon steel fell near Pollard's correlation, but the HSLA steels exhibited slightly higher ductility ratios than Pollard's data would have predicted. The relationship between weld-metal hardness and ductility ratio may not hold for steels having significantly different chemistries or processing. For example, it has been shown[2] that an HSLA steel produced without inclusion shape control exhibits lower cross-tension strength (and a lower ductility ratio) as a result of lamellar tearing during the cross-tension test.

Inclusion shape control would not be expected to significantly influence the weld-metal hardness, yet the size and shape of nonmetallic inclusions has been stated to have an important effect on spot-weld ductility.[2] The two HSLA steels in this investigation had been treated with cerium (Table 1) to modify the inclusion shape; therefore, this factor should not have influenced the ductility ratio in these steels.

Welding Current Range and Current Load

The width and level of the welding current range must be considered in practical applications. This is because the weld current cannot be controlled precisely and, since various types of materials are welded, it is desirable that the current levels be somewhat similar. The welding current ranges defined by weld interface diameters determined in tensile shear and cross-tension tests are presented in Fig. 11. Note that the welding current range for the HSLA steels is generally under that of the SAE 1008 steel.

The upper limit of the welding current range is generally regarded as the minimum current that causes expulsion.[1,2] However, the criterion for the lower limit is not well established. Some specifications define the lower limit as that current which produces a minimum acceptable button size. Since the weld-button diameter has good correlation with the tensile shear strength and cross-tension strength, this is a reasonable criterion for the lower current limit.

In this work, the minimum acceptable button size was 0.22 inch (5.6 mm), as defined in an automotive specification[1] for this thickness of steel. Although the lower current limits were determined from button sizes measured on tensile shear and cross-tension specimens, these values would be reasonable estimates of the lower limits from other types of tests.

The two HSLA steels tested exceeded a 2000 A range required by an automotive specification.[1] The welding current range for the HSLA steels also completely overlapped the 12.1 to 13.1 kA range as required for this thickness in an automotive specification.

Metallography and Hardness

As no significant effect of electrode force was observed, photomicrographs representing one electrode force for each material are presented in Fig. 12. The microstructures are representative of the center of the weld nugget and contained the following constituents: (a) Mn-Mo-Cb, upper bainite + martensite (or lower bainite); (b) V-N,

Fig. 12—Comparison of three weld-nugget microstructures: left (a)—Mn-Mo-Cb; center (b)—V-N; and right (c)—SAE 1008 steel. 2% nital, ×1000

martensite (or lower bainite); and (c) SAE 1008, ferrite + upper bainite.

The results of the microhardness measurements are presented in Fig. 13. The highest hardness of both the weld metal and base metal was exhibited by the V-N steel. The hardness level at the center of the weld metal was approximately 400 HV_{500} for V-N, 300 HV_{500} for Mn-Mo-Cb, and 200 HV_{500} for SAE 1008 steel—regardless of the electrode force.

General Discussion

In the present work the welding current and electrode force were the primary process variables. The results indicate that welding current is a significant variable, while electrode force does not significantly affect the spot weldability on flat coupons. Because of higher spring-back forces, however, the HSLA steels generally require a higher electrode force.

The welding current range of the Mn-Mo-Cb steel was very similar in width and level to that of the V-N steel and wider than that of the SAE 1008 carbon steel. However, the welding current ranges for both HSLA steels were located at a lower current level than that of the SAE 1008 carbon steel. Considering the relatively wide welding current range and the favorable strength properties compared to SAE 1008 steel, these HSLA steels can be spot welded by adjusting the welding current to a lower level while still using the other welding conditions normally employed when welding conventional low-carbon steels of the same thickness.

The spot weldability of the Mn-Mo-Cb and V-N steels met all the requirements of an automotive specification,[1] including the ductility (peel) test, current-range test, and current-level test. The mechanical properties of spot welds in both the Mn-Mo-Cb and V-N steels were at least comparable or better than those of the SAE 1008 steel. Their advantage over low-carbon steel was their higher tensile shear strength.

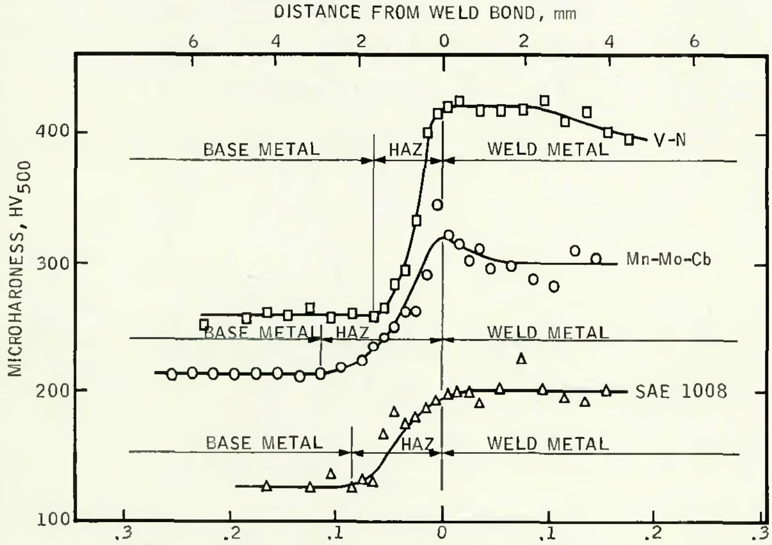


Fig. 13—Hardness profiles of spot welds

Conclusions

1. The Mn-Mo-Cb and V-N steels tested could be spot welded using the same electrode size, electrode force, and welding time as for an SAE 1008 steel of the same thickness. The welding current level of the HSLA steels was lower than that of the low-carbon steel.

2. The spot weldability of the Mn-Mo-Cb steel was similar to that of the V-N steel with respect to the width and level of the welding current range.

3. The ductility ratio of the two HSLA steels was significantly lower than that of the SAE 1008 carbon steel.

4. The Mn-Mo-Cb steel exhibited a slightly higher ductility ratio and a lower weld nugget hardness than the V-N steel.

5. Both the Mn-Mo-Cb steel and V-N steel exhibited good spot weldability compared to the SAE 1008 steel; these HSLA steels have a wider welding current range, higher tensile shear strength, and equal or higher cross-tension strength.

6. The HSLA steels would be expected to pass all requirements of an automotive specification, i.e., ductility test, welding current-range test, and welding current-level test.

7. Good correlation was obtained between tensile shear strength and weld-button area when interface failure occurred and between cross-tension strength and weld-button diameter when pullout failure occurred.

Future Work

The fatigue strength of an HSLA spot weld is usually higher than that of a plain-carbon steel spot weld in low-cycle (high-load) tests, but in the high-cycle regime it approaches the same low level of plain-carbon steels.[2-4] It is not anticipated that the Mn-Mo-Cb steel would behave differently from the other HSLA steels in this type of test, but this aspect should be examined.

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