Spot Weld Properties When Welding With Expulsion—A Comparative Study

Reduced strength does not necessarily result when resistance spot welds are made under expulsion conditions

BY M. KIMCHI

ABSTRACT. A high proportion of resistance spot welds are made under expulsion conditions and have been assumed to be of lower strength and quality than welds made without expulsion. This paper provides comparative data on weld properties made with and without expulsion under various welding conditions.

Although increased indentation occurs when expulsion conditions are used, the welds are not necessarily of reduced strength. At welding currents just over the expulsion criterion normally used for reference, there is generally some loss of strength on the order of 5%. With further current increases, considerable growth in the nugget size and strength are obtained. The strength increase and indentation depend to a great extent on the electrode geometry and other welding conditions. Elastic stress analysis to support the experimental results is presented.

Welding under expulsion conditions in the range where improved weld strength is obtained causes rapid electrode deterioration. The extent and consequences of the electrode deterioration are likewise dependent on electrode geometry. This study involved only bare high strength low alloy (HSLA) and low carbon steels; the results should not be extrapolated to any of the coated steels.

Introduction

Excessive heating in resistance welding results in metal expulsion during the welding operation. Good welding practice is considered to be one that operates just below initial expulsion. While published resistance spot welding schedules assume that welds are made without expulsion, this seldom occurs in production where a high percentage of spot welds are actually made with expulsion. Investigators and text books state that expulsion welds are undesirable and weak because "further increase in current does not increase the size of the spot, but seriously injures its metallurgical structure and markedly increases the indentation" (Ref. 1). However, no evidence or data to support the above statements were found in the literature.

The investigation described in this paper was undertaken to provide comparative test data on weld properties made with and without expulsion under various welding conditions. Resistance welding electrode life when welding with expulsion is also a part of this study. Only bare HSLA and low carbon steels were considered. An elastic stress analysis providing support to the experimental strength results is presented in the Appendix.

Procedure

Materials used in this investigation and their chemical compositions are presented in Table 1. Welding schedules used are listed in Table 2. Welds were made just below the expulsion point for each particular schedule, and the welding current was subsequently increased in increments to well above the expulsion point. Spot weld sample geometry is shown in Fig. 1.

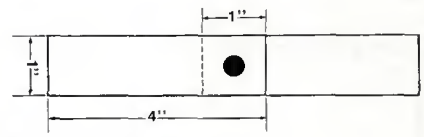

Fig. 1—Spot weld specimen

Weld indentation was measured, and the samples were tested in tensile-shear to determine the ultimate load. A number of tension-tension fatigue tests were conducted with constant load amplitude to a maximum value of 450 lb (204 N) and R = 0.2 (R = minimum stress/max stress). The cyclic loading rate was 20 Hz.

Welds were examined metallographically to verify nugget size determined by the peel test; welds were also inspected for defects and examined for failure modes. To analyze the weld nugget growth during expulsion welding, additional instrumented tests were made to determine the welding current cycle where expulsion first occurred.

Electrode life tests were performed in order to evaluate the effect of welding with expulsion on electrode deterioration and to determine the consequences of extensive use of expulsion welding in production.

Results and Discussion

Figure 2 shows the effect of welding above the expulsion point on spot weld strength using flat faced (FF) truncated electrodes with a 30 deg side angle. At a current setting just above the expulsion point, a reduction in strength on the order of 5% is apparent. At higher current settings, significant improvement in tension-shear strength was observed. The relative effect of electrode force is also presented in Fig. 2. As would be expected, increasing the electrode force increases the current level required to reach expulsion and also increases the strength of the weld made just below the expulsion point.

The effect of weld time on tension-shear strength is shown in Fig. 3. Stronger welds were made with the longer weld time schedule (16 cycles) just below and

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Table 1—Materials and Chemical Composition, %

Material and thickness	C	S	Cr	Ni	Mn	Mo	Cu	Si	Cb	P	Al
0.038 in. (0.97 mm) low carbon	.038	.020	.012	.020	.35	.006	.047	<.003	<.002	.005	<.004
0.036 in. (0.91 mm) HSLA[a]	.054	.011	.015	.028	.70	.007	.039	.360	.040	.008	.020
0.098 in. (2.49 mm) HSLA[b]	.031	.016	.009	.022	.50	.008	.036	.045	.120	.009	.042

(a) Cb-bearing high strength low alloy steel—50 ksi (348 MPa) yield strength.
(b) Cb-bearing high strength low alloy steel—70 ksi (482 MPa) yield strength.

Table 2—Spot Welding Schedules[a]

Welding schedule	Material[b] and thickness	Electrode geometry[c][d], deg	Electrode diameter, in.	Welding force lb	Weld time cycles
A	0.036 in. HSLA	30	0.25	800	12
B	0.036 in. HSLA	30	0.25	450	12
C	0.036 in. HSLA	30	0.25	800	18
D	0.036 in. HSLA	45	0.25	800	12
E	0.036 in. HSLA	3 in. radius		800	12
F	0.036 in. HSLA	3 in. radius		450	12
G	0.038 in. LC	30	0.25	450	12
H	0.038 in. LC	30	0.25	800	12
I	0.038 in. LC	45	0.25	800	12
J	0.038 in. LC	30	0.25	450	16
K	0.038 in. LC	45	0.25	450	9
L	0.038 in. LC	3 in. radius		450	12
M	0.038 in. LC	3 in. radius		800	12
N	0.098 in. HSLA	45	0.25	800	12
O	0.098 in. HSLA	45	0.25	450	12
P	0.098 in. HSLA	20	0.31	1400	24

(a) 1 in. = 25.4 mm; lb × 4.448222 = newtons (N)
(b) HSLA—high strength low alloy; LC—low carbon.
(c) Electrodes that are not radius faced, are flat faced truncated electrodes and the side angle is specified.
(d) Electrodes are RWMA Class 2 in all cases.

well above initial expulsion. However, a greater reduction in strength of the weld made at initial expulsion is evident. No loss of strength at initial expulsion was observed using the short weld time (9 cycles—see schedule K, Table 2). Figure 4 illustrates in detail the effect of welding at initial expulsion on weld strength. In addition to the reduced strength shown, erratic results were recorded when welds were made at this current level.

Figures 5 and 6 clearly indicate that welding well above the expulsion point produced welds with better tension-shear strength; they also indicate that the failure load for a spot weld is a function of nugget diameter.

The effect of electrode geometry on spot weld strength is presented in Fig. 7. Higher weld strength was obtained using the 30 deg rather than the 45 deg flat faced (FF) truncated electrode. Using electrodes with the smaller side angle (30 deg) tends to limit the indentation and helps to contain and mechanically hold the molten nugget. It also seems to provide better support to the edges of flat faced electrodes and hence increase electrode tip life.

The amount of indentation was shown to have little effect on spot weld strength. Although measurements indicated up to 55% indentation with 800 lb (363 N) electrode force, significant improvement in weld strength was clearly shown as a result of larger weld diam-

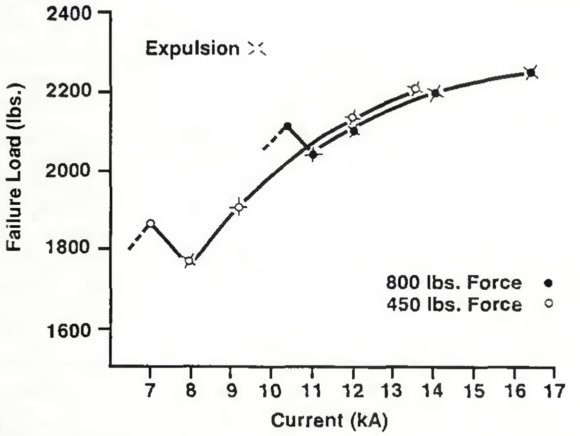

Fig. 2—Tension-shear strength of spot welds made at various current levels when welding with expulsion—effect of electrode force. Material—0.036 in. thick HSLA steel; weld time—12 cycles; electrodes—0.25 in. diameter 30 deg FF

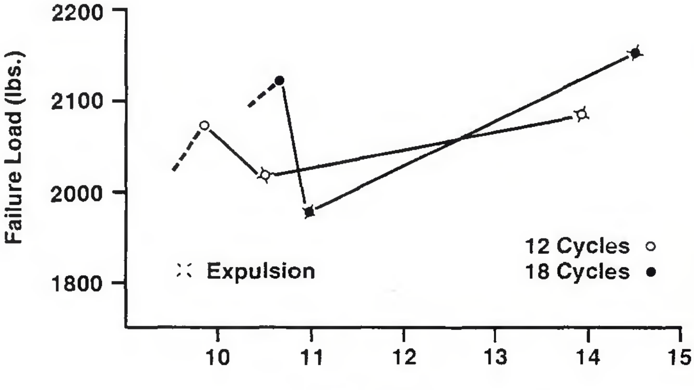

Fig. 3—Tension-shear strength vs. current—effect of weld time. Material—0.036 in. thick HSLA steel; electrode force—800 lb (3.6 kN); electrodes—0.25 in. diameter 30 deg FF

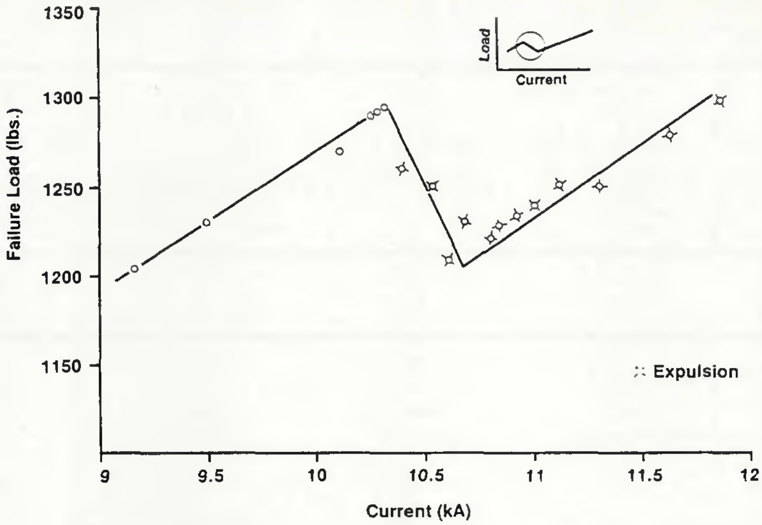

Fig. 4 — Detailed analysis of the initial expulsion portion of the tension-shear curve. Material — 0.038 in. thick low carbon steel; electrode force — 450 lb (2 kN); electrodes — 0.25 in. diameter 30 deg FF

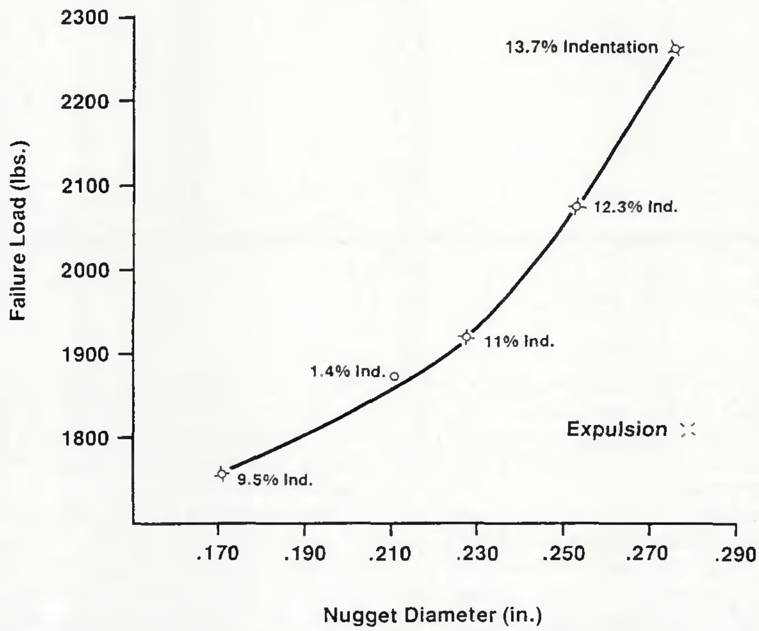

Fig. 6 — Tension-shear strength as a function of weld nugget diameter when welding with expulsion; note the percent indentation. Material — 0.036 in. thick HSLA steel; weld time — 12 cycles; electrode force — 450 lb (2 kN); electrodes — 0.25 diameter 30 deg FF

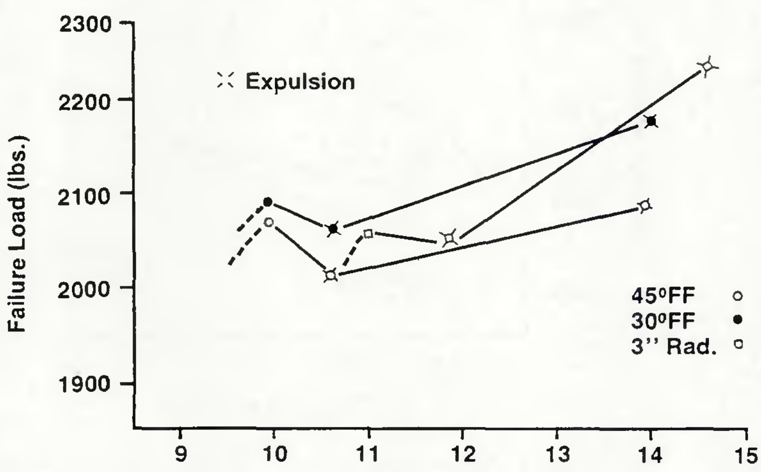

Fig. 7 — Tension-shear strength vs. current — effect of electrode geometry. Material — 0.036 in. thick HSLA steel; weld time — 12 cycles; electrode force — 800 lb (3.6 kN)

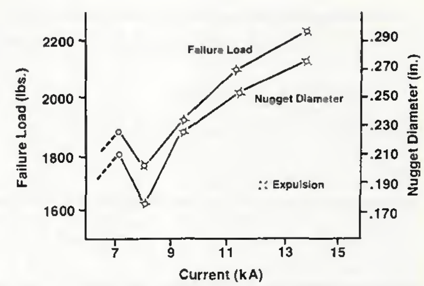

Fig. 5 — Correlation between weld nugget diameter and tension-shear strength. Material — 0.036 in. thick HSLA steel; weld time — 12 cycles, electrode force — 450 lb (2 kn); electrodes — 0.25 in. diameter 30 deg FF

eters. The elastic stress analysis presented in the Appendix suggests that weld diameter is the main controlling factor of weld strength rather than indentation.

Figure 8 shows the effect of electrode geometry on the indentation. Indentation was greatest with the flat faced 45 deg truncated electrode and least with the 3 in. (76 mm) radius faced electrode for the same welding parameters. Severe indentation did not affect fatigue properties since significant improvement in fatigue life (up to 68%) when welding with expulsion was obtained. Tension-tension fatigue properties are presented in Fig. 9.

In the case where the current is set just above the value that causes initial expulsion, the expulsion may occur toward the end of the weld time with little subsequent current flow. At higher welding current levels, expulsion tends to occur earlier in the welding period with current flowing during the remaining weld time — Fig. 10. This effect is believed to cause the weld nugget to further increase in size. Figure 11 shows metallographic sections of welds made at different expulsion levels. Increased nugget diameter and electrode indentation with higher expulsion current is apparent.

Figure 12 shows weld specimens made at low and high expulsion current settings after failure in tension-shear. The fracture location of the weld made with low expulsion current occurs at the indentation edge through the reduced section (case B in the Appendix). The fracture of the weld made with the high expulsion current is through the full thickness of the base metal (case A in the Appendix). Note that the nugget diameter exceeds the electrode diameter and that the fracture occurs outside the indented area. Measurements show a 0.275 in. (6.98 mm) weld diameter for the high expulsion current weld, while the nugget diameter of the low expulsion current weld was 0.172 in. (4.37 mm). Both welds were made with 0.25 in. (6.35 mm) face diameter electrodes.

Electrode life tests when welding with expulsion (15% heat above the initial

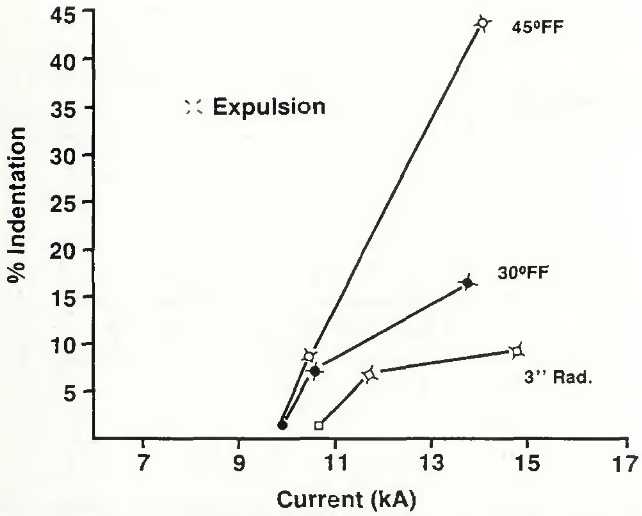

Fig. 8 — Electrode indentation at various current levels and the effect of electrode geometry. Material — 0.036 in. thick HSLA steel; weld time — 12 cycles; electrode force — 800 lb (3.6 kN)

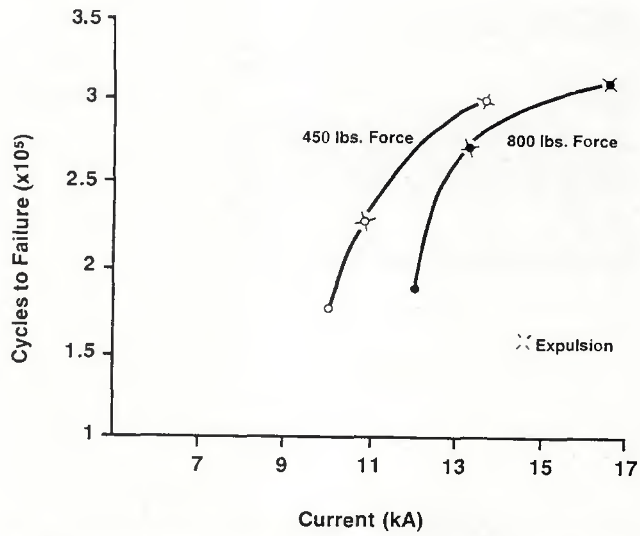

Fig. 9 — Tension-tension fatigue life of expulsion welds at maximum load of 450 lb (2.0 kN) and the ratio of minimum stress to maximum stress = 0.2 — effect of electrode force. Material — 0.038 in. thick low carbon; weld time — 12 cycles; electrodes — 0.25 in. diameter 30 deg FF. X6 (reduced 52% on reproduction)

expulsion point) using 0.25 in. (6.35 mm) diameter 45 deg truncated electrode, results in rapid deterioration of the electrode; nugget diameter dropped from 0.27 in. (6.86 mm) to 0.20 in. (5.08 mm) after 500 welds and then stabilized. Surface expulsion was observed, and the expulsion current changed from 10,500 to 7,500 amperes (A) after 1,500 welds. No significant change in nugget size was observed using 3 in. (76 mm) radius faced electrodes in the life test. After 2000 welds the expulsion current increased from 9,700 to 11,500 A.

The apparent behavior of the two electrode geometries can be explained by the different deterioration phenomena shown in Fig. 13. In the case of a flat faced electrode, deterioration begins at point E (edge) and results in decreased electrode diameter and increased current density — Fig. 14. In the case of radius faced electrodes, deterioration begins at point C (center) and results in increased electrode diameter and decreased current density.

In addition to shorter electrode tip life when welding with expulsion in production, the amount of indentation may present a problem if appearance is an important factor. For such applications, indentation greater than 5% is usually considered undesirable. The excessive sparking characteristic of expulsion spot welding should be recognized as a potential safety hazard.

Conclusions

1. Electrode indentation is not of prime importance in determining spot weld strength.

2. An increase in welding current well above the initial expulsion point results in an increase in nugget diameter with attendant increase in shear strength.

3. Spot welds made with current levels above the initial expulsion point showed significant improvement (up to 68%) in fatigue life due to an increase in nugget diameter.

4. For current settings below and just above the expulsion point, better weld strength was obtained using 800 lb (363 N) welding force than the 450 lb (204 N)

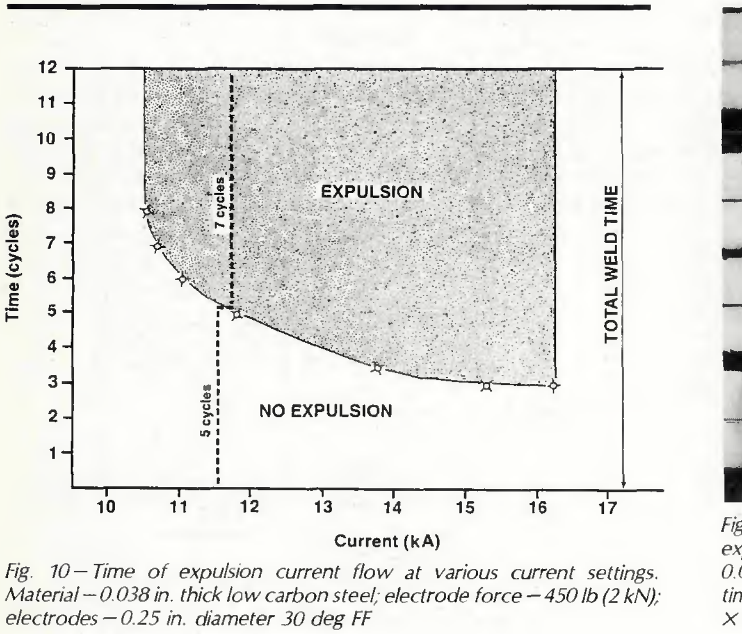

Fig. 10 — Time of expulsion current flow at various current settings. Material — 0.038 in. thick low carbon steel; electrode force — 450 lb (2 kN); electrodes — 0.25 in. diameter 30 deg FF

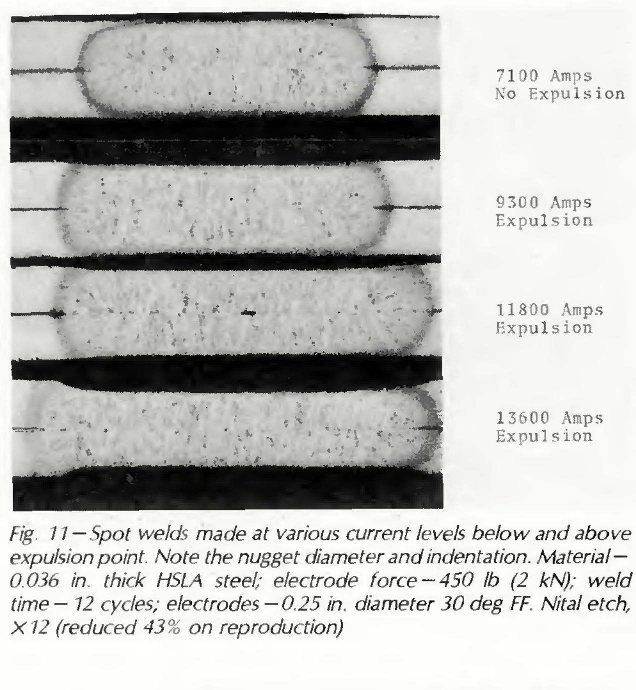

Fig. 11 — Spot welds made at various current levels below and above expulsion point. Note the nugget diameter and indentation. Material — 0.036 in. thick HSLA steel; electrode force — 450 lb (2 kN); weld time — 12 cycles; electrodes — 0.25 in. diameter 30 deg FF. Nital etch, X12 (reduced 43% on reproduction)

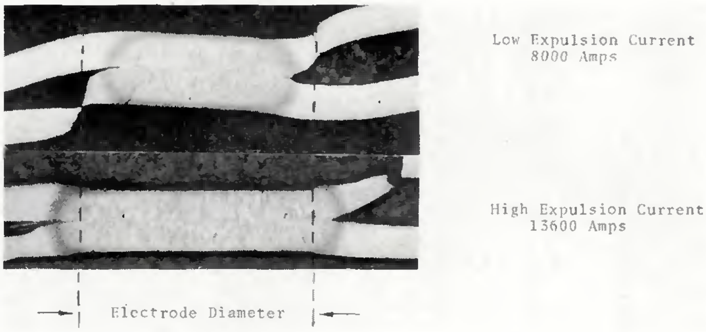

Fig. 12 — Welds made with different expulsion current settings. Note the failure location in relation to the electrode indentation and nugget diameter. Material — 0.036 in. thick HSLA steel; electrode force — 450 lb (2 kN); weld time — 12 cycles; electrodes — 0.25 in. diameter 30 deg FF. Nital etch, X10 (reduced 50% on reproduction)

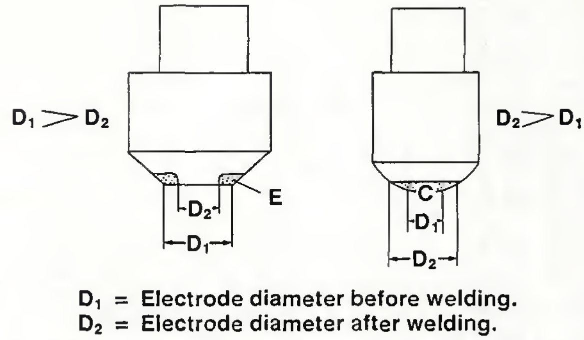

Fig. 13 — Differences in deterioration of flat-faced and radius-faced electrodes

Fig. 14 — Electrode deterioration — 0.25 in. (6.35 mm) diameter flat face, 45 deg truncated electrode after 1500 welds

recommended for this gauge of steel.

5. Stronger welds were made with longer weld time below and above the initial expulsion point. However, lower strength at initial expulsion was obtained. No loss in strength was observed using the short weld time schedule.

6. Electrode indentation was greatest with the 45 deg truncated electrodes, least with the 3 in. (76 mm) radius faced electrode, while the indentation with 30 deg truncated electrodes was intermediate.

7. Just above the expulsion point, expulsion occurs near the end of the welding time. At higher current levels, expulsion tends to occur earlier in the welding period, and the weld continues to grow during the remaining welding time period.

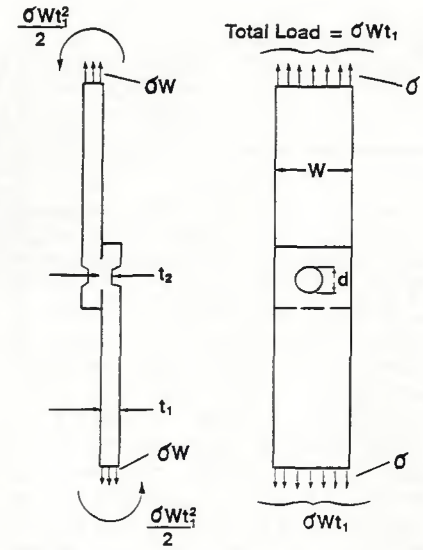

Fig. 15 — Tension-shear specimen

8. When welding with expulsion, two accelerated electrode deterioration mechanisms were observed. In flat-faced electrodes deterioration starts at the edges, while in radius-faced electrodes deterioration begins at the center.

9. Although good results were reported in the radius faced electrode life test, more work is needed to determine the feasibility of using expulsion welding in production. Welding with expulsion using flat-faced electrodes is the least desirable of the two alternatives.

References

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Appendix

The following elastic stress analysis is intended to explain the tension-shear experimental results demonstrating the relative importance of weld sample variables which influence tension-shear

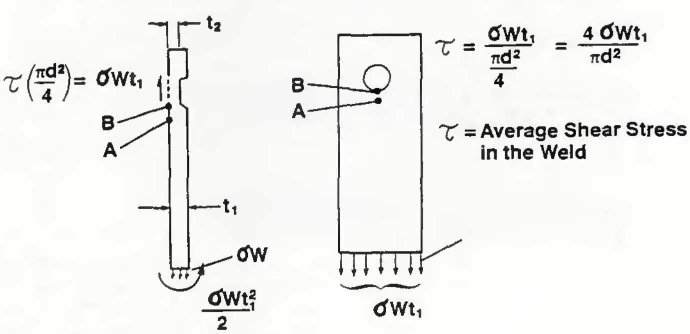

Fig. 16 — Specimen bottom half

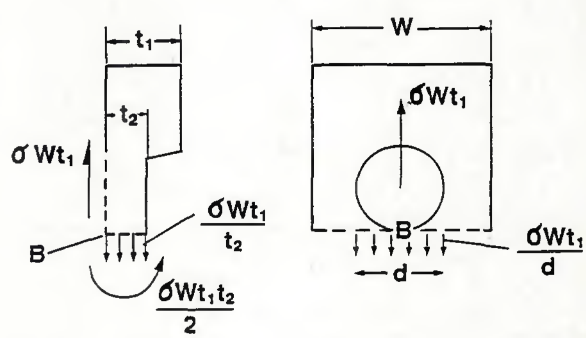

Fig. 17 — Analysis of failure at point B

strength. Depicted in Fig. 15 is a tension-shear specimen for which:

w = specimen width,
d = nugget diameter,
t_1 = sheet thickness,
t_2 = ½ nugget thickness,
σ = average applied stress,
σw = load per unit length in thickness direction,
$\sigma w t_1$ = total applied load, and
$(\sigma\, w t_1)^2/2$ = end bending moment due to offset of lap joint.

One can consider the static equilibrium of the bottom half of a tension-shear spot welded specimen as shown in Fig. 16. Here two failure locations are possible—points A and B. Although the stress at point B (σ_B) is greater than the stress at point A (σ_A), the ultimate tensile strength may be greater at point B due to metallurgical changes in the heat-affected zone (HAZ).

Failure at Point B

Referring to Fig. 17, total elastic stress at B, σ_B, is determined by summing the axial and bending contributions:

$$\sigma_{axial} = \frac{\text{total load}}{\text{effective cross section area at B}}$$

$$= \frac{\sigma w t_1}{d t_2}$$

$$\sigma_{bending} = \frac{(\text{bending moment at B}) \times (\text{distance from centroid to B})}{\text{effective moment of inertia}}$$

$$= \frac{\dfrac{\sigma w t_1\, t_2}{2} \times \dfrac{t_2}{2}}{\dfrac{1}{12}\, d t_2^3}$$

$$\sigma B =$$

$$\sigma axial + \sigma bending = \frac{\sigma w t_1}{d t_2} + \frac{\sigma W t_1 \dfrac{t_2}{2}\dfrac{t_2}{2}}{\dfrac{1}{12}\, d t_2^3}$$

$$\sigma B = \sigma\left(\frac{W}{d}\right)\left(\frac{t_1}{t_2}\right) + 3\,\sigma\left(\frac{W}{d}\right)\left(\frac{t_1}{t_2}\right)$$

$$\sigma B = 4\,\sigma\left(\frac{W}{d}\right)\left(\frac{t_1}{t_2}\right)$$

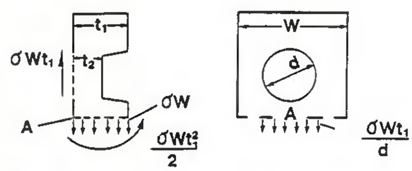

Fig. 18—Analysis of failure at point A

Failure at Point A

Since point A is slightly removed from the weld nugget, consideration must be given to the portion of the sheet at A effective in resisting the applied stress. Since t_1/t_2 is significantly less than W/d, the distance from the weld at which the full t_1 is effective is significantly less than the distance at which full w is effective. Thus, the effective thickness and width are assumed to be t_1 and d, respectively:

$$\sigma_A = \sigma_{axial} + \sigma_{bending} = \frac{\sigma W t_1}{d t_1} + \frac{\sigma w \dfrac{t_1^2}{2}\dfrac{t_1}{2}}{\dfrac{1}{12}\, d t_1^3}$$

$$\sigma_A = \sigma\left(\frac{W}{d}\right) + 3\,\sigma\left(\frac{W}{d}\right)$$

$$\sigma_A = 4\,\sigma\left(\frac{W}{d}\right)$$

The above equation suggests that failure loads are proportional to the nugget diameter when failure occurs at point A. In most of the tests, failure did occur at point A, and calculated proportions of loads and nugget diameters showed close agreement.

The above is an elastic analysis valid up to first yield. However, it does provide insight into what parameters are significant in determining ultimate tensile-shear loads.