SIZING OF SPOT WELDS BY ELASTIC/PLASTIC ANALYSIS

R. A. Smith

**Cambridge University Engineering Department, Trumpington Street,
Cambridge CB2 1PZ, UK**

ABSTRACT

A widely used quality control test for spot welds is the cross tension test in which welded pieces are forced apart. Depending on the relative size of the weld diameter and sheet thickness, failure occurs by either the pulling of a slug of metal or by cracking across the weld junction. This paper uses a combined fracture mechanics/plasticity analysis to predict a rational basis for weld size selection.

KEYWORDS

Spot welds, spot weld sizing, fracture of interfaces, slug pulling.

INTRODUCTION

Many mass production industries use resistance spot welding to fabricate sheet metals. A prime example is afforded by the automobile industry - a modern car can have as many as 5,000 spot welds in its construction. With weight saving and consequent fuel conservation now vitally important, high strength low alloy steels are being used in smaller sheet thicknesses than their mild steel counterparts. For a given sheet thickness correct choice of weld size is vitally important. The size must be sufficiently large to give strength and impact resistance to the connection, but not too large otherwise larger scale welding machinery is needed, the product appearance is marred and a larger area of metal is wasted in the land between adjacent welds.

Spot welds can fail in two markedly different ways. Fracture across the interface occurs for small weld diameter to sheet thickness ratios, whilst for larger sizes a plug can be pulled from one of the sheets. The first type of fracture is considered unsatisfactory and various sizing recommendations for its avoidance have been made. Weld performance and quality is checked in two kinds of tests - a shear (peel) test pulled tangentially to the sheet direction or by using a cross tension specimen in which the arms of a centrally spot welded cruciform specimen are gripped and pulled apart in a direction normal to the sheet thickness, Fig. 1.

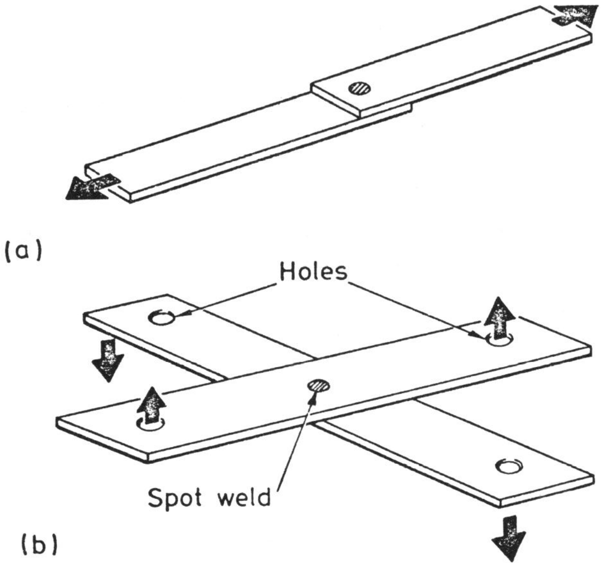

Fig. 1 (a) Shear (peel) test
(b) Cross tension test for spot weld performance

This paper concentrates on this latter test, in an attempt to derive a rational size selection rule which takes into account both possible types of failure and the relevant material properties which govern such failures.

PRESENT SELECTION RULES

Some considerable debate exists in the literature as to the optimum size of sheet thickness to weld diameter. The relevant British standard (BS 1140) recommends a diameter of $5\sqrt{t}$, where t is the sheet thickness in mm., a relationship derived from the work of Tucker (1943). Janota (1972) obtained a relationship $d = 3.6t$, from the results of peel tests. Numerous other relationships have been proposed and are discussed, for example, by Williams and Jones (1979). The only similarity between the various proposals are their empirical origins, derived from extensive experimental testing and their supposed blanket applicability, independent of the varying properties of the materials to which they are applied. In the only paper to attempt an analysis of the peel test, Vanden Bossche (1977), the suggestion was made that the properties of welds in HSLA steels could be improved by making them larger than the current rules indicate, their size being determined by the strength of the parent weld.

FAILURE MODES IN THE CROSS-TENSION TEST

A cross section of a typical spot weld is shown in Fig. 2. For small weld diameter to thickness ratios, failure occurs at low load levels, the geometry of the connection being largely unchanged. The weld therefore acts as a circular neck surrounded by a circumferential sharp crack. At a critical load, the crack tip advances through the typically brittle metal of the heat affected zone (H.A.Z.) Fig. 3. This differs somewhat from the classical brittle fracture instability in that the crack is advancing into tougher material towards the centre of the nugget where S.E.M. evidence shows the fracture is essentially ductile, Williams and Jones (1979). However, this effect is usually overcome by the large increase in the near crack tip stresses as the remaining uncracked area decreases.

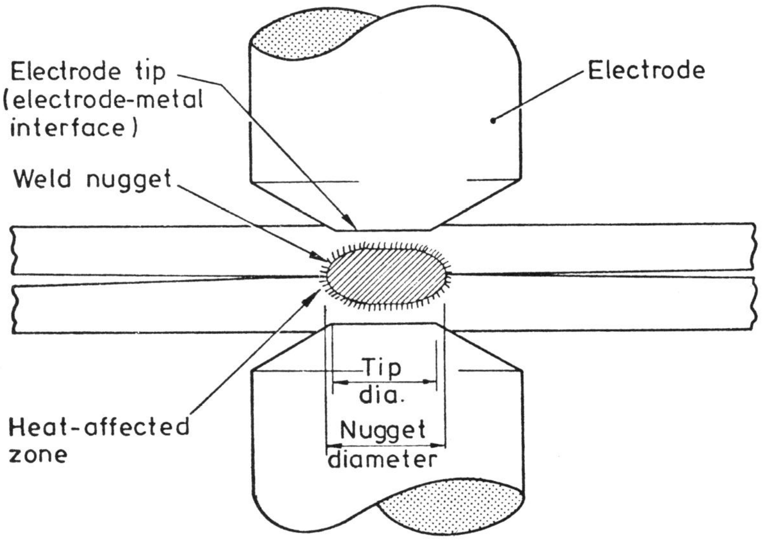

Fig. 2 Cross section of a typical spot weld

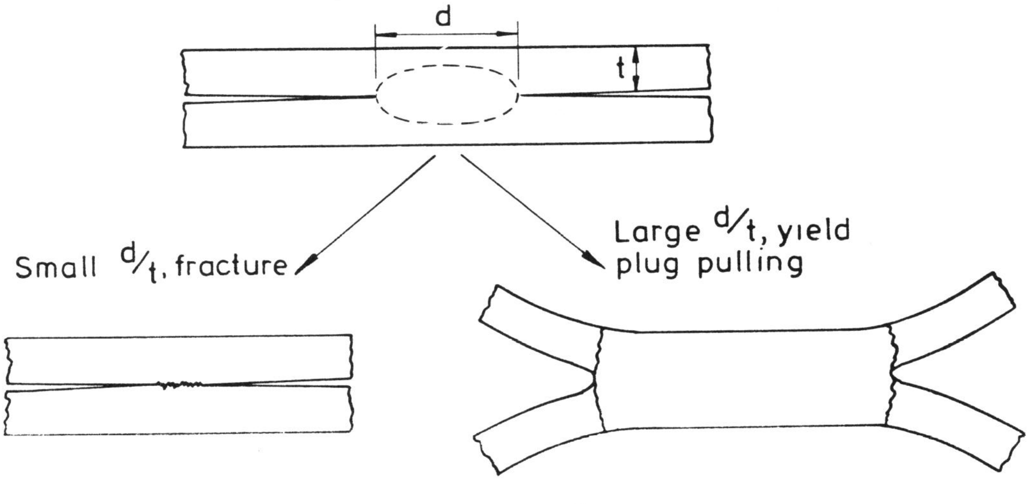

Fig. 3 Fracture and yielding types of spot weld failure

For large diameter to thickness ratios, failure occurs at much higher load levels with considerable bending deformation of the arms supporting the weld. This leads to a blunting of the crack tip, a rotation of the maximum shear stress axis to the through thickness direction of the sheet and failure by net section yield leading to plug formation.

MODELS OF FAILURE MODES

The fracturing of the weld nugget can be modelled by a sharp linear elastic fracture mechanics approach. Failure is initiated when the Mode I stress intensity factor at the circumference of the weld nugget reaches a value equal to the local toughness of the weld metal i.e.

$$K_1 = K_c \tag{1}$$

Experimental observations show that the geometry of the weld is largely maintained for this type of failure, thus justifying the sharp crack approach. The major difficulty lies in obtaining an expression for the stress intensity factor. In the absence of an exact model, the results of Tada et al (1973) have been adopted. Strictly speaking these apply to point tensile loads applied along the axis of symmetry of the weld (Fig. 4), and to an internal joint between semi-infinite plates. Both these conditions will tend to underestimate the actual stress intensity factor obtained when the load is fed from the cruciform arms of the test piece into the weld junction and the plates are of finite thickness. However since the theory will be shown to rely only on the variation of the above solution over a small thickness/diameter range, little serious error will be introduced.

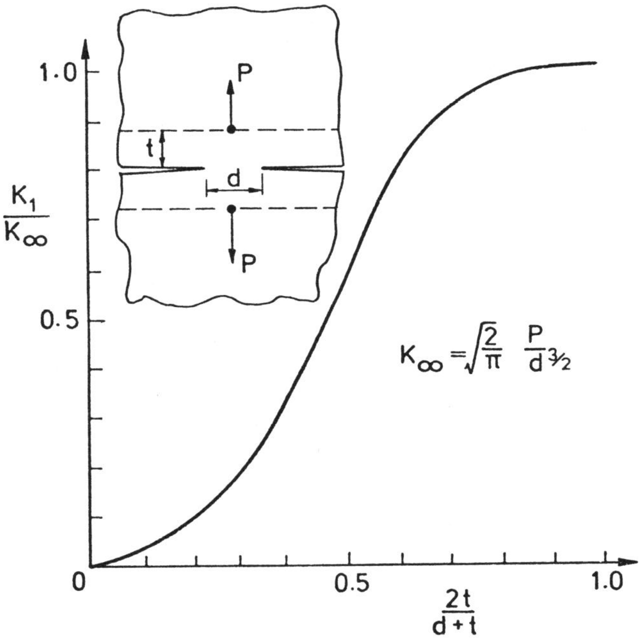

Fig. 4 Stress intensity factors for a point loaded circumferential neck crack, Tada et al (1973)

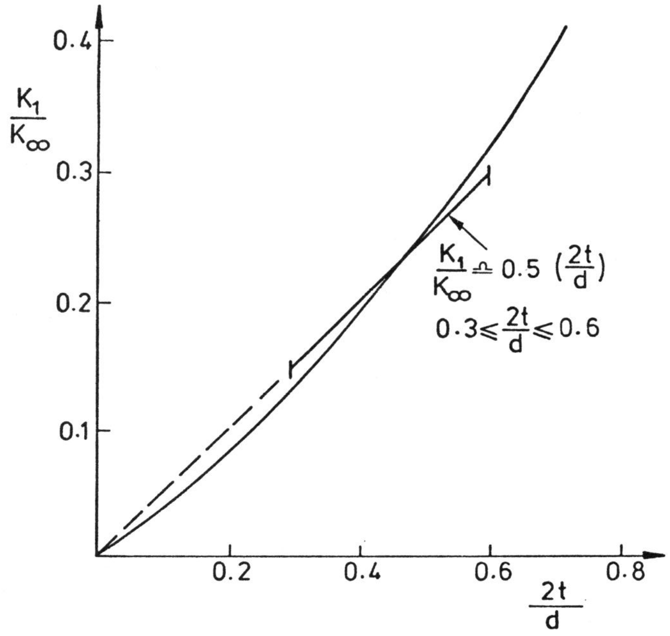

Fig. 5 Approximation of the Tada solution

Over the small range of sizes of practical interest (Fig. 5) we may linearise the above solution by the approximation:

$$\frac{K_1}{K_\infty} = 0.5 \left(\frac{2t}{d}\right)$$

where t is the sheet thickness, and d the spot weld diameter. This approximation is always in error by less than 8% in the range $0.3 \leqslant (2t/d) \leqslant 0.6$. Since $K_\infty = \sqrt{2/\pi}\ \sqrt{P/d^{3/2}}$, we obtain:

$$K_1 = 0.8 \frac{P}{d^{5/2}} \tag{2}$$

where P is the applied load. Hence by using (2) in (1) we obtain the load for fracture, P_F,

$$P_F = 1.25\ K_c \frac{d^{5/2}}{t} \tag{3}$$

For failure by plug pulling, the blunting/yield mechanism shown in Fig. 3 is operative. A simultaneous lower and upper bound solution for the net section yield is given by equating the shear stress round the circumference of a cylindrical plug of diameter d, equal to the weld nugget diameter, to the shear yield stress of the sheet, i.e.

$$\sigma = \frac{P_y}{\pi d.2t} = \tau_y$$

thus giving the yield load, P_y,

$$P_y = 6.28\ t\ d\ \tau_y \tag{4}$$

The critical weld size which is just at the point of failing by plug pulling is that given by equating the fracture and yield loads, equations (3) and (4)

$$d_c = 2.93 \left(\frac{\tau_y}{K_c}\right)^{2/3} t^{4/3} \qquad (5)$$

EVALUATION OF THE PROPOSED DESIGN RULE

We note that the proposed design rule, equation (5) contains the materials constants, τ_y governing yield and K_c governing fracture. As an example we can evaluate equation (5) from the data provided by Rivett (1979) and reproduced in Fig. (6). The material used was a cold rolled mild steel, 1.18 mm thick, 264 MN/m^2 tensile yield and 328 MN/m^2 U.T.S. The carbon equivalent content was 0.120. The toughness for this material can be obtained from the small diameter/ thickness tests where the failure was clearly by interface fracture. From Fig.(6), for d = 4 mm, $P_F = 3.5$ kN, hence from equation (3) rearranged: $K_c = 103$ $Nmm^{-3/2}$. Using a value for the shear flow stress of $(\sigma_y + \sigma_{UTS})/4 = 148$ N/mm^2, the critical diameter can be found from equation (6),

$$d_c = 2.93 \left(\frac{148}{103}\right)^{2/3} 1.18^{4/3}$$

$$= \underline{4.65 \text{ mm}}$$

This value, together with the corresponding calculated failure load of 5.09 kN is shown on Fig. (6) to give a clear separation of the fracture and yield failure modes.

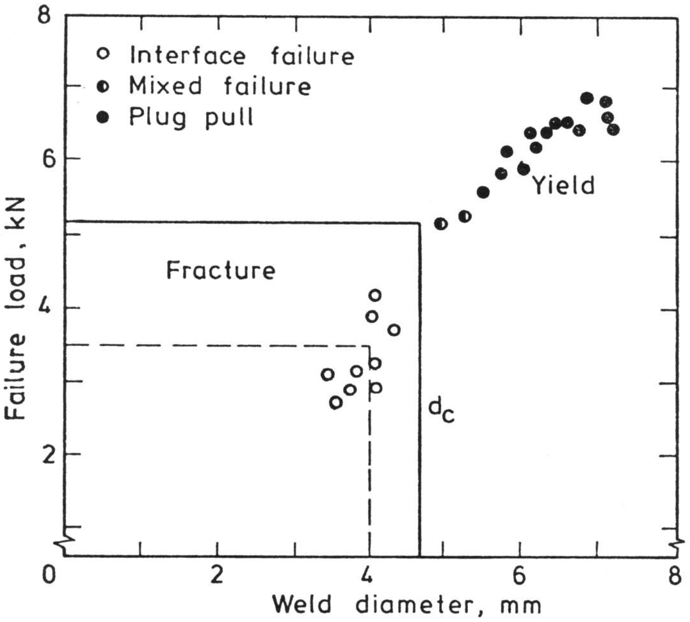

Fig. 6 Experimental weld strength data, Rivett (1979)

Using these calculated material constants, for this particular steel, equation (5) reduces to

$$d_c = 3.7\ t^{4/3} \quad (d_c,\ t \text{ in mm.}) \tag{6}$$

This is plotted in Fig. (7), together with the existing rules from BS 1140 and Janota (1972). It can be seen that for larger values of sheet thickness, the proposed rule indicates larger values of weld diameters which may overcome the deficiencies of the present rules. Furthermore, the new proposal has the virtue of incorporating relevant material properties, which will vary with different classes of materials.

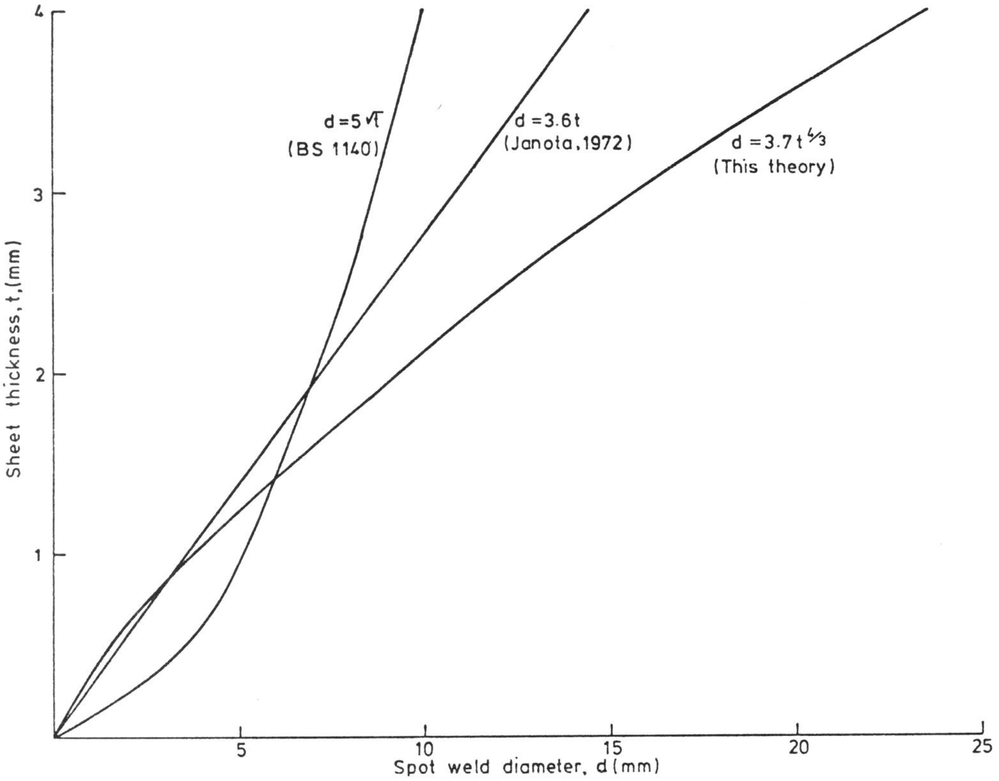

Fig. 7 Comparison of spot weld sizing rules

CONCLUSIONS

A new sizing criterion for spot welds has been developed. The new proposal incorporates material properties which control both fracture and yield. Preliminary tests on existing experimental data suggest that the new rule indicates the use of greater weld sizes for thicker sheets than the present rules. Further experimental results on different materials over a wide range of thicknesses are being undertaken. A study of the approximations in the stress analysis employed is also being made.

REFERENCES

British Standard 1140 (1957).
Janota, M (1972), II W Doc III - 455-72.
Rivett, R.M. (1979), Welding Institute Research Bulletin, 20, 235-239.
Tada, H., Paris, P. and Irwin, G. (1973), The Stress Analysis of Cracks Handbook 25.5, Del Research Corp., St. Louis, Missouri.
Tucker, N.A., (1943), Sheet Metal Industries, 17, 1051-1053.
Vanden Bossche, D.J., (1977), SAE Paper 770214.
Williams, N.T. and Jones, T.B., (1977), Metal Construction, 11 541-546.