

Failure mode of spot welds: interfacial versus pullout

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Spot welds produced via resistance welding have been widely used in the joining of sheet metal for autobodies since the 1950s. Every modern car contains over 2000 spot welds. Failure of the spot weld is therefore an important concern in relation to autobody durability and safety design. Spot welds can fail in two completely distinct modes, namely, nugget pullout failure and interfacial failure. In the present paper, it is first shown that the nugget pullout failure is caused by plastic collapse and the interfacial failure is governed by crack or fracture mechanics. These two failure mechanisms compete with each other and failure of a spot weld occurs when the fracture criterion for one of the mechanisms is satisfied first. Test data from available literature are used to validate the theoretical predictions. Recommendations are made for minimum weld nugget size for a given sheet metal thickness so that nugget pullout failure, the acceptable mode of failure in industry, is ensured. STWJ/334

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INTRODUCTION

Spot welds produced via resistance welding have been widely used in the joining of sheet metal for autobodies since the 1950s. A modern vehicle typically contains 2000–5000 spot welds. For a given sheet metal thickness, the correct selection of weld size is critical. A subsized spot weld may present inadequate strength in overload or crash scenarios and reduced fatigue life under normal operation of the vehicle. An oversized nugget requires large scale welding machinery and is thus of higher cost to fabricate.

Various industry standards recommend the optimum or minimum size of the spot weld for a given sheet metal thickness. For example, the American Welding Society (AWS), Society of Automotive Engineering (SAE), and the American National Standards Institute (ANSI),¹ together recommend a weld nugget diameter given by

$$d = 4\sqrt{t} \quad (1)$$

for steels, where d and t are the weld nugget diameter and thickness, respectively (in mm). A minimum nugget diameter

$$d = 0.69(1.65t - 0.007)^{1/2} \quad (2)$$

and nominal nugget diameter

$$d = 0.86(1.65t - 0.007)^{1/2} \quad (3)$$

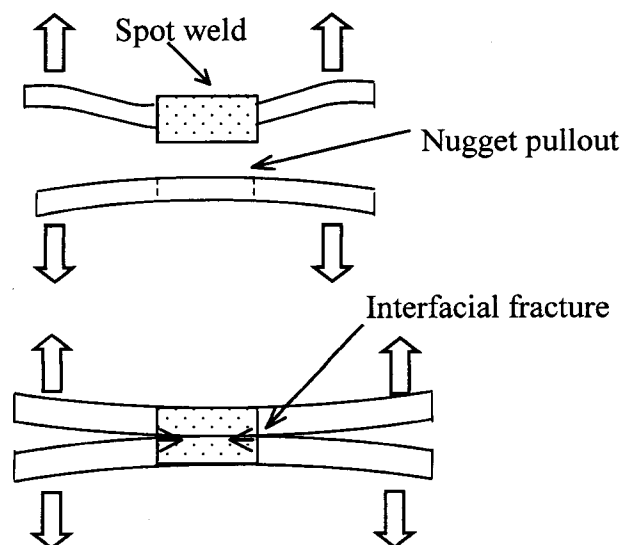
where d and t are in inches, are also frequently used in the

automotive industry.² Note that all these recommended formulae in industry standards are empirical in nature and are derived from extensive experimental testing. An interesting point in relation to these empirical formulae is that they are independent of the varying properties of the materials to which they are applied. It will be shown below that this independence is indeed observed for a range of steels from traditional low carbon mild sheet steels to high strength sheet steels.

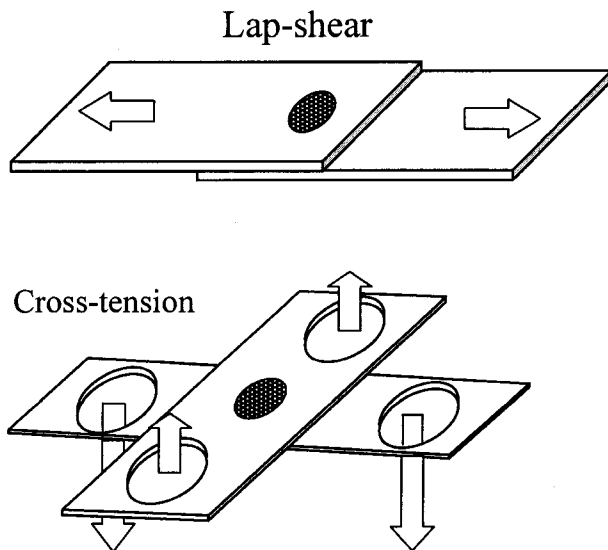
Spot welds can fail in two markedly different modes. As shown in Fig. 1, fracture via crack propagation through the weld nugget, often occurring in a small weld, is known as interfacial failure. In a large weld, nugget pullout failure may occur, in which the weld nugget is completely pulled out from one of the metal sheets, leaving a circular hole in the sheet. Interfacial failure, which is associated with lower load carrying capacity and considerably less energy absorption capability, is considered unsatisfactory and industry standards^{1,2} are often designed to avoid its occurrence.

Detailed stress analysis of spot welds was recently published by Radaj³ and Zhang.⁴ Failure mechanisms in spot welds under monotonic load were studied by Zuniga and Sheppard.⁵ Mixed mode testing and analysis were performed by Lin *et al.*⁶ Smith⁷ used a novel, yet simple approach to investigate the competition between the two failure modes of spot welds. Some test data were presented by Ewing *et al.*,² Lee *et al.*,⁸ and VandenBossche.⁹

In strength or weldability tests on spot welded joints, lap shear samples or cross tension samples, as shown in Fig. 2, are often used. The tests using lap shear geometry provide the 'shear strength', and the tests using cross tension samples give the 'tensile strength' of the joint normal to the sheet surface.



1 Two distinct failure modes of spot welds—nugget pull-out and interfacial failure



2 Typical test samples—lap shear and cross tension

In the present paper, the failure of cross tension samples is analysed. The approach reported by Smith⁷ was followed and extended. The two failure modes, i.e. interfacial and nugget pullout, are first studied individually using fracture mechanics and plastic collapse, respectively. The competition of these two failure modes is then investigated. Based on the analysis, the minimum weld nugget diameter for a given sheet metal thickness to ensure a nugget pullout failure, as opposed to interfacial failure, is obtained. Experimental data are provided to verify the analytical formula. It is further shown that the results can be applied to both cross tension and lap shear samples and a variety of steels as well. Finally, discussions are presented relating the present results to current industry standards for sizing the weld nugget.

GOVERNING EQUATIONS FOR INTERFACIAL FAILURE

Interfacial failure of a spot weld, as shown in Fig. 1, is essentially crack propagation or fracture of the weld nugget under mode I conditions, using the terminology of fracture mechanics. A precise relationship linking the applied load to a stress intensity factor, essential to a fracture mechanics study, is not readily available for such a geometry. Smith⁷ adopted the stress intensity factor relation from Tada *et al.*,¹⁰ as shown in Fig. 3, for the spot weld geometry. In Fig. 3, t is used to represent the sheet thickness, d the weld nugget diameter, and P the remotely applied tensile load to the weld. The functional relationship between the applied load P and the stress intensity factor K_I is then¹⁰

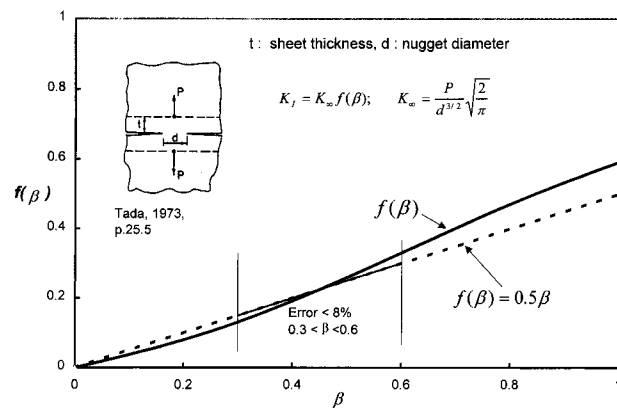
$$K_I = \frac{P}{d^{3/2}} \left(\frac{2}{\pi} \right)^{1/2} f(\beta) \quad (4)$$

where

$$f(\beta) = \frac{2}{\pi} \left\{ \tan^{-1} \beta + \frac{\beta}{1+\beta^2} \left[1 - 0.714 \left(\frac{2}{1+\beta^2} \right) \right] \right\}$$

$$\text{and } \beta = \frac{2t}{d} \quad (5)$$

Note that the function $f(\beta)$ is highly non-linear with respect to t and d , which renders impossible a simple relation of the nugget diameter to sheet thickness. Smith,⁷ however, first observed that the function, when plotted against $\beta = 2t/d$, is nearly linear, as shown in Fig. 3. Therefore, an approximate, linearised form $f(\beta) \cong 0.5\beta$ was selected, which is also plotted in Fig. 3. It can be seen that this approximation is



3 Approximate stress intensity factors for spot welds (after Ref. 10)

reasonably accurate especially in the range $0.3 \leq (2t/d) \leq 0.6$, a range satisfied by most automotive spot welds. Incorporating this approximation, equation (4) has the simple form

$$P = 1.25 K_I \frac{d^{5/2}}{t} \quad (6)$$

At failure, the stress intensity factor K_I is equal to the critical stress intensity factor K_{IC} or fracture toughness. Equation (6) then can be written as

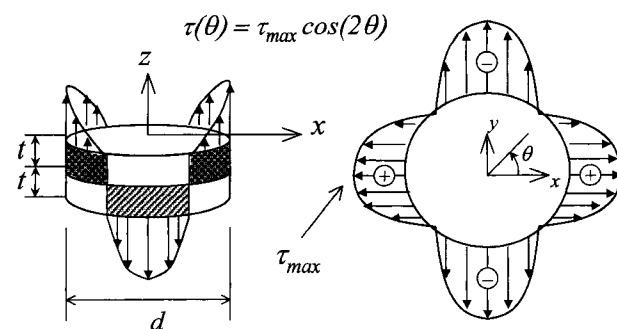
$$P_f = 1.25 K_{IC} \frac{d^{5/2}}{t} \quad (7)$$

where P_f is the failure load and K_{IC} is the fracture toughness of the weld nugget material.

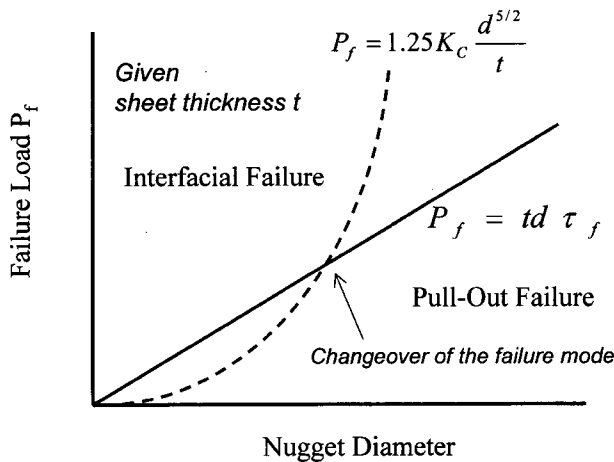
GOVERNING EQUATIONS FOR NUGGET PULLOUT FAILURE

The hardness of the nugget of a spot weld in sheet steels used in the automotive industry is typically two to three times that of the base metal. Consequently, the nugget functions mechanically as a rigid button embedded in a ductile metal sheet. The pullout failure of a spot weld in a cross tension sample is thus predominantly plastic shear or plastic collapse around the circumference of the weld nugget in the heat affected zone. The stress distribution for such a sample geometry is highly complex. A simplified engineering analysis has recently been proposed by Chao.¹¹ It assumes a rigid weld nugget and considers only the predominant (shear) stress around the nugget. As shown in Fig. 4, using the assumed stress distribution, the far field applied tensile load P is related to the local stresses according to

$$P = \int_{-\pi/4}^{\pi/4} \tau(\theta) 2rt \, d\theta = td \tau_{\max} \quad (8)$$



4 Approximate stress distributions around weld nugget in cross tension test sample



5 Schematic diagram showing competition between interfacial failure (broken line) and nugget pullout failure (solid line)

where $\tau(\theta)$ is the local shear stress, r is the radius of the nugget, and τ_{\max} is the maximum shear stress at the weld nugget. At the initiation of fracture, equation (8) becomes

$$P_f = t d \tau_f \quad (9)$$

where P_f is the failure load and τ_f is the fracture stress in shear or shear strength of the heat affected zone.

COMPETITION OF TWO FAILURE MODES

The two distinct failure modes, i.e. the interfacial mode governed by equation (7) and the nugget pullout mode governed by equation (9), compete with each other. During loading, the failure mode is determined by which condition, associated with each failure mode, is met first. As shown in Fig. 5, as the load is increased, the failure mode will be interfacial for small weld nuggets, but pullout for large weld nuggets for a given sheet thickness. The transition occurs when equation (7) equals equation (9), at the intersection of the two curves shown in Fig. 5. Equating equations (7) and (9) and letting $d = d_{cr}$ yields

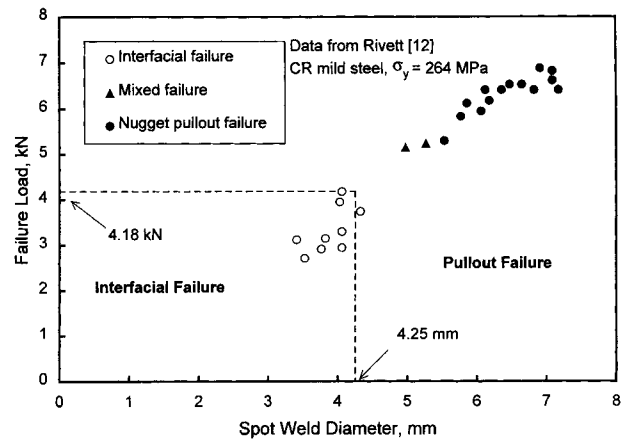
$$d_{cr} = 0.86 \left(\frac{\tau_f}{K_C} \right)^{2/3} t^{4/3} \quad (10)$$

where d_{cr} is defined as the critical weld nugget diameter for a given sheet thickness. The criterion for fracture mode transition of any spot weld can therefore be stated as follows: for a given sheet thickness t , interfacial failure will occur for diameters $d < d_{cr}$ and nugget pullout will occur for $d > d_{cr}$.

Equation (10) contains two material properties, namely, the shear strength τ_f and fracture toughness K_C . By varying the welding schedule appropriately to achieve different weld diameters, performing tensile tests, and recording the failure load, τ_f can be determined using equation (9) from those spot welds which fail by nugget pullout, which is generally observed for large weld nuggets. Further, K_C can be determined using equation (7) from those welds that fail via the interfacial mode, which is generally observed for small weld nuggets.

If the exact function $f(\beta)$ given in equation (5) is used, in conjunction with equations (4), (7), and (9), the critical weld nugget diameter for a given sheet thickness is then obtained as

$$d_{cr} = 0.673 \left[\frac{f(\beta) \tau_f}{K_C} \right]^2 t^2 \quad (11)$$



6 Test data from Ref. 12, showing interfacial and nugget pullout failures: predicted critical nugget diameter of 4.25 mm from equation (12) is also shown

COMPARISONS WITH TEST DATA

Comparisons of failure mode transition for cross tension geometry

Rivett¹² performed a series of tests to study the failure of spot welds on a cold rolled mild steel, 1.18 mm in thickness, with 264 MPa tensile yield stress and 328 MPa ultimate tensile strength (UTS). The carbon equivalent content was 0.12. The test data (failure load and nugget diameter) containing interfacial and pullout failure modes, as well as mixed failure modes, are reproduced and plotted in Fig. 6.

Using equation (9), the shear fracture stress, averaged from all the test data in Fig. 6 that correspond to failure in pullout mode, is determined as 833.4 MPa. Using equation (7), the fracture toughness, averaged from all the test data in Fig. 6 that correspond to failure in interfacial mode, is 105.6 N mm^{-3/2}. Using equation (10), the critical weld nugget diameter d_{cr} (in mm) is then given by

$$d_{cr} = 3.41 t^{4/3} \quad (12)$$

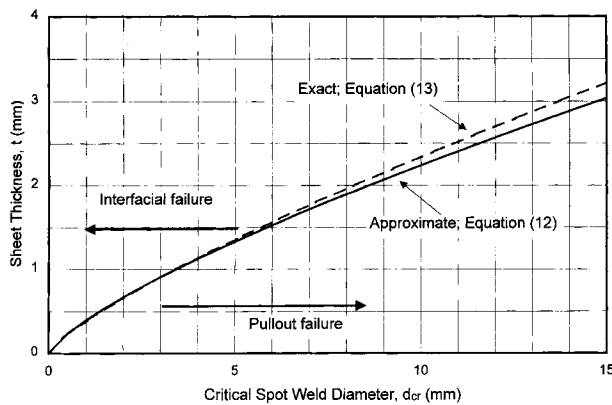
Since $t = 1.18$ mm, equation (12) gives the critical nugget diameter as $d_{cr} = 4.25$ mm. Accordingly the failure load is 4.18 kN using either equation (7) or equation (9). These calculated values of critical nugget diameter and failure load are included in Fig. 6, which clearly distinguishes the two failure modes.

It can be shown that the fracture toughness value is 116.5 N mm^{-3/2} if the exact equations (4) and (5) are used. The critical nugget diameter for this particular material, using equation (11), is then

$$d_{cr} = 32.6 t^2 f^2(\beta) \quad (13)$$

Both equations (12) and (13) are plotted in Fig. 7. Note that equation (13) is a complex function of d , since d is also embedded in the function $f(\beta)$, in addition to appearing in the left hand side of the equation. MathCAD (Mathsoft Engineering and Education Inc., Cambridge, MA, USA) was used to plot equation (13) in Fig. 7. In contrast, equation (12) is much simpler than equation (13). The difference between the two equations is negligible, as shown in Fig. 7. For practical applications, the approximate formula (12) is adequate and is therefore recommended.

To validate the model further, test data from Ewing *et al.*² were plotted in Fig. 8. Two materials were used in Ref. 2, namely, SAE 1006 (a galvanised mild steel, 1.3 mm thickness, 252 MPa tensile yield stress, and 327 MPa UTS) and SAE 960X (a galvanised high strength steel, 1.4 mm thickness, 424 MPa tensile yield stress, and 501 MPa UTS). Test results from static and impact tests on three standard spot weld test sample geometries, i.e. lap shear, cross



7 Critical spot weld diameters as function of sheet thickness, using both exact equation (13) and approximate equation (12)

tension, and coach peel, were reported in Ref. 2. The data in Fig. 8 are from Fig. 9 of Ref. 2, and are those obtained from cross tension samples in both quasistatic and low rate impact tests. In designing the weld, Ewing *et al.*² used a nominal welding schedule to produce the 'nominal' weld, shown as schedule 2. The welding schedule was intentionally changed to a higher current to produce an oversized weld nugget, reported as schedule 3, and a lower current to produce an undersized weld nugget, reported as schedule 1. All welds from schedule 1 failed in the interfacial mode, whereas welds from both schedules 2 and 3 failed in the nugget pullout mode, under quasistatic as well as impact loading for all test sample geometries.

Following the same procedure as was used for the data of Rivett,¹² the average shear fracture stress τ_f is obtained as 805 MPa, and the average fracture toughness K_C as $92.14 \text{ N mm}^{-3/2}$. All test data shown in Fig. 8, except the lowest point at $d=5 \text{ mm}$ that is obviously from a defective weld, are used to obtain these averages. The critical weld nugget diameter d_{cr} , using equation (10), is therefore given by (in mm)

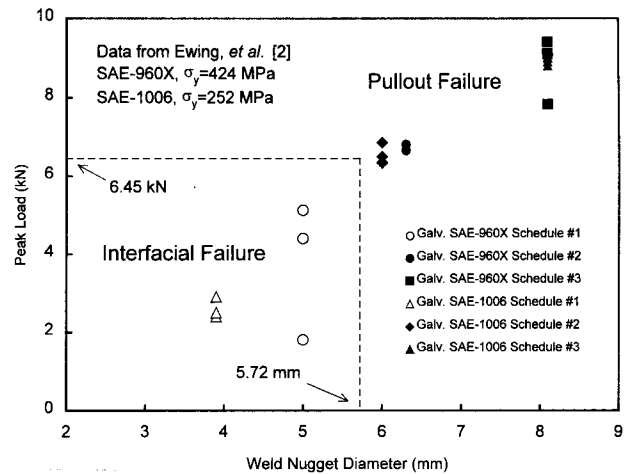
$$d_{cr} = 3.65t^{4/3} \quad (14)$$

Note that the two materials investigated give similar values because their failure loads were nearly identical, as shown in Fig. 8. Using $t=1.4 \text{ mm}$, the critical nugget diameter is therefore $d_{cr}=5.72 \text{ mm}$ according to equation (14). The corresponding failure load is 6.45 kN using either of equations (7) and (9). These values of critical nugget diameter and failure load are included in Fig. 8, which again clearly distinguishes the two failure modes.

Comparisons of failure mode transition for lap shear geometry

Both the mathematical analysis in the preceding sections and the comparisons in the above subsection for the failure mode transition from interfacial to nugget pullout are for the cross tension sample geometry. In practice, spot welds are subjected to other types of loading, such as remote shear. An obvious question is therefore that of whether equation (10) is adequate in predicting failure modes under other types of loading. To answer this question, the present predictions are compared with test data from lap shear samples in this subsection.

VandenBossche⁹ performed a series of tests to study the failure of spot welds using lap shear test samples. Fifteen different sheet steel materials having yield strengths varying from 206 MPa (30 kg in^{-2}) to 655 MPa (95 kg in^{-2}) and thicknesses from 0.64 to 2.26 mm were tested. The critical nugget diameters from twenty test groups were identified from tests and reported. They are plotted in Fig. 9 along



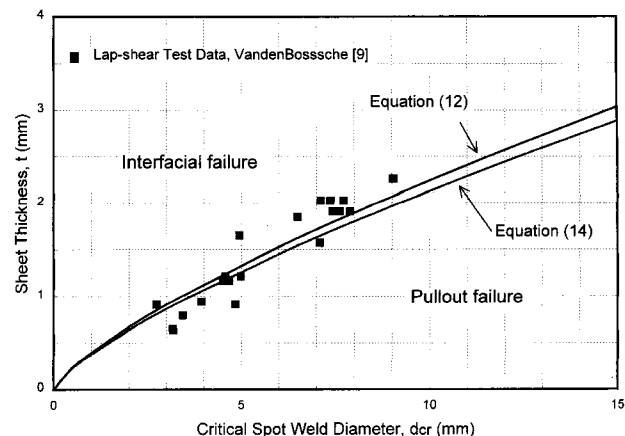
8 Test data from Ref. 2, showing interfacial and pullout failure regimes of spot welds: critical nugget diameter of 5.72 mm, predicted by equation (14), is also shown

with the predictions based on equations (12) and (14). As shown in Fig. 9, the predictions are remarkably accurate. The comparisons shown in Fig. 9 demonstrate that equations (12) and (14) can be used in predicting the failure mode for (i) both tensile and shear loading of spot welds and (ii) different grades of sheet steels. This conclusion is further corroborated by the test results from Ewing *et al.*,² in which all welds fabricated using welding schedule 1 (2 and 3) failed in the interfacial (nugget pullout) mode for all lap shear, cross tension, and coach peel sample geometries. Furthermore, the same failure modes were observed under impact conditions for all these sample geometries.²

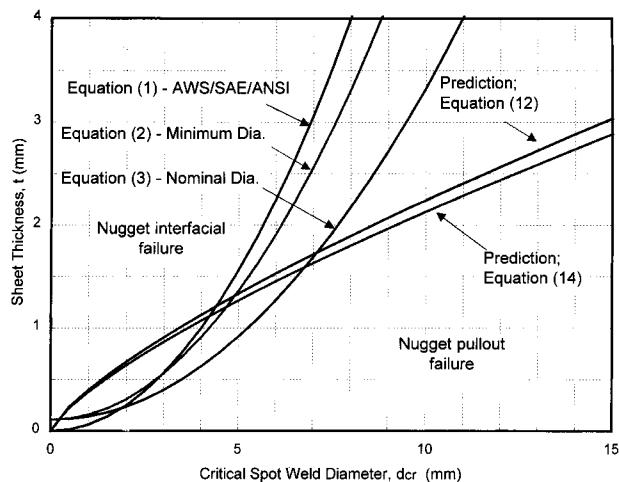
DISCUSSION

Material dependence of prediction

It can be seen from the curves plotted in Fig. 9 that the predictions from equations (12) and (14) are very similar, despite being derived from three different steels having different strength properties. Furthermore, the test data from VandenBossche⁹ are from 15 different sheet steels having yield strengths varying from 206 MPa (30 kg in^{-2}) low carbon mild steel to 655 MPa (95 kg in^{-2}) very high strength steel. This close correlation indicates that the prediction of critical nugget diameter based on equation (10) is weakly dependent upon the grade of steel. As such, either



9 Comparison of predicted critical nugget diameters for transition of failure mode, obtained using equations (12) and (14), with test data (from Ref. 9) for lap shear samples



10 Comparison of theoretical predictions with industrial standards

of equations (12) and (14) can be used for most of the steels. This conclusion could be due to the elimination of the effect of material property through the term (τ_f/K_C) in equation (10). Indeed, this conclusion coincides with the industry practice, i.e. the recommended empirical formulae in various industry standards, e.g. equations (1)–(3), are independent of the varying properties of the materials.

Close examination of equation (10) indicates that if this formula is to be universally applicable to a variety of steels, it requires the ratio (τ_f/K_C) to be a constant. Through comparisons (e.g. Figs. 6, 8, and 9), the test data cited in the present paper appear to support this conclusion. Further studies to validate this point, involving more materials, would certainly be worthwhile.

Comparisons with industrial standards

Figure 10 shows the critical weld sizes predicted from equations (12) and (14), and those recommended from industrial standards, i.e. the AWS/SAE/ANSI¹ standard (equation (1)), minimum weld diameter criterion² (equation (2)), and nominal weld diameter criterion² (equation (3)).

Note that in autobody applications, sheet metal thickness normally lies in the range 0.5–2.5 mm. The comparison shown in Fig. 10 indicates that (i) the equation for nominal nugget diameter, equation (3), is the most conservative among the industrial standards, (ii) the industrial standards are conservative for sheet thicknesses up to $t \approx 1.2$ –1.5 mm, (iii) equations (12) and (14) are close to the industrial standards in the range $t = 1.0$ –1.5 mm, and (iv) equations (12) and (14) diverge from the industrial standards with increasing sheet thickness beyond $t = 1.5$ mm.

Relatively, it appears that although the industrial standards are conservative in predicting the failure mode for thin gauge steel sheets, i.e. $t < 1.2$ mm, they are not sufficient to predict the failure mode for thick steel sheets, i.e. $t > 1.2$ mm. In particular, the recommendation by AWS/SAE/ANSI,¹ equation (1), could yield an inadequate weld size for thicker steel sheets. This is evidenced by the test data shown in Fig. 9 near $t = 2$ mm.

CONCLUSIONS

A mathematical analysis combining the fracture mechanics and plastic collapse is presented to predict the failure mode, either nugget pullout or interfacial, of resistance spot welds. The analysis yields a critical weld nugget diameter, which distinguishes the two failure modes. The analytical results are validated through comparison with available test data. Furthermore, it is shown that (i) the failure mode can be predicted using the derived formula for spot welds under either tensile (cross tension samples) or shear (lap shear samples) loads, and (ii) the analytical results may be applied to many different grades of steel varying from low carbon mild steels to high strength steels as well as under either quasistatic or impact loading conditions.

By comparison with test data and industry standards for sizing weld nuggets, the results obtained in the present paper suggest a simple and improved formula for predicting the transition of failure mode from pullout to interfacial. With further validation, e.g. more test data for thin ($t < 1.0$ mm) gauge steels, equation (12) or equation (14) could be recommended for sizing of spot welds in steel sheets for automotive industry applications.

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