

Effects of Expulsion in Spot Welding of Cold Rolled Sheet Steels

Z. Han and J.E. Indacochea

The effects of expulsion on microstructure and tensile shear strength of spot welds have been investigated for a high-strength cold rolled sheet steel. Spot welds with expulsion are characteristic for a "double image" near the fusion line, an equiaxed dendritic grain zone along the faying surface, and deep indentations on the outer surfaces. Microstructural examinations and tensile shear tests of spot welding specimens were conducted to determine the correlation between microstructure and strength. It was found that the equiaxed dendritic structure was associated with significant solidification cracking. Fractography on tensile specimens reveals that brittle failure is associated with an equiaxed microstructure. Furthermore, the surface indentation will change the stress at the nugget edge, and deep surface indentations are expected to promote premature failure.

Keywords
cold rolled steel, microscopy, welding

1. Introduction

RESISTANCE spot welding is a common industrial process for the joining of sheet metals. It has wide application in mass production, where long production runs and consistent welds are required. The automotive and appliance industries are the major users of this welding process.

Thermomechanical processing and joining with resistance spot welding is a complex and difficult phenomena that entails mechanical, electrical, thermal, and metallurgical factors. To develop the proper automation mechanisms and to improve the productivity of resistance spot welded parts, an understanding of this complicated welding process is important. Several studies have been performed,[1-6] either experimental or numerical, with the objective of improving the automated system and thus increasing productivity. Some studies, particularly the numerical ones, use mathematical models to analyze the process and use computers in their application of complex mathematical formulations to simulate the resistance spot welding process. However, nugget development and weld soundness are apparently influenced by the sheet metal composition and thermal history. Consequently, in assessing the soundness of the weld nugget and consistency of this welding process, the microstructure and weld appearance should be correlated with the welding parameters.

High-strength sheet steels are supplied in either the hot or cold rolled condition. Generally, their high strength over that of plain-carbon sheet steels is obtained by addition of alloying elements associated with controlled mill processing. However, the addition of alloying elements causes an obvious degradation of weldability because of the increased electrical resistivity and lower thermal conductivity. As a result, weld nugget growth is largely accelerated, and the occurrence of expulsion is easier. In industry, the lobe curve is used to represent the weldability of sheet steels; a narrow acceptable welding region for high-strength sheet steels is expected. A high proportion of resistance spot welds are made under expulsion conditions. Usually, spot welding with expulsion results in strength degradation of spot welds, reduction in nugget size,[7] poor surface appearance, and rapid electrode deterioration.[8] However, the influence of expulsion on weld nugget microstructure as well as its relation with strength degradation has received little attention. The objective of this investigation is to provide further understanding of the changes in microstructure and joint integrity brought about by expulsion and ultimately its effect on strength.

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2. Experimental Procedure

The material used in this investigation was a high-strength cold rolled sheet steel 2.18 mm (0.086 in.) thick. The composition and tensile strength of this material are shown in Tables 1 and 2. The sheet steel was cut into coupons 102.0 mm (4.0 in.) long and 25.4 mm (1.0 in.) wide. Spot welds were produced by varying the process parameters (weld cycle, weld current, and electrode force). A Sciaky press-type 100-kV·A single-phase resistance welding machine was used. The electrodes were a class II copper alloy (99.2% Cu and 0.8% Cr) based on the Resistance Welder Manufacturers Association standard, with a 45° truncated cone tip.

Table 1 Steel composition

Composition, wt%						
C	Si	Mn	S	P	Al	N
0.12	0.27	1.42	0.003	0.023	0.053	0.010

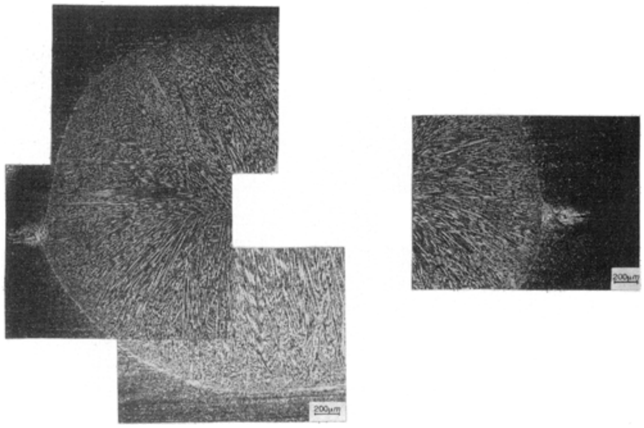

Fig. 1 Microstructure of a typical spot weld with no expulsion.

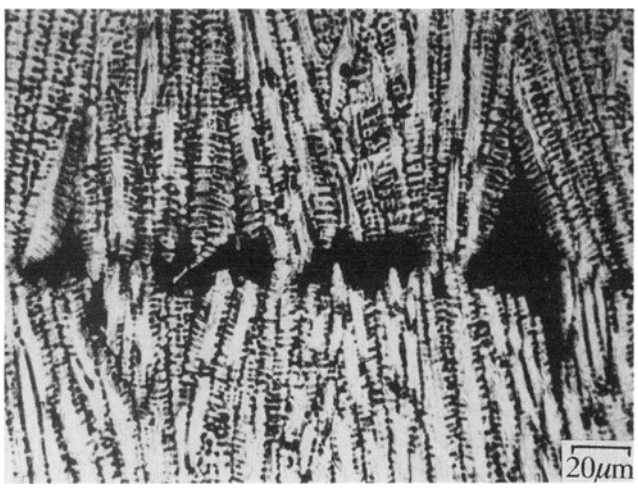

Fig. 2 Solidification cracks present between columnar dendrites and by faying surface.

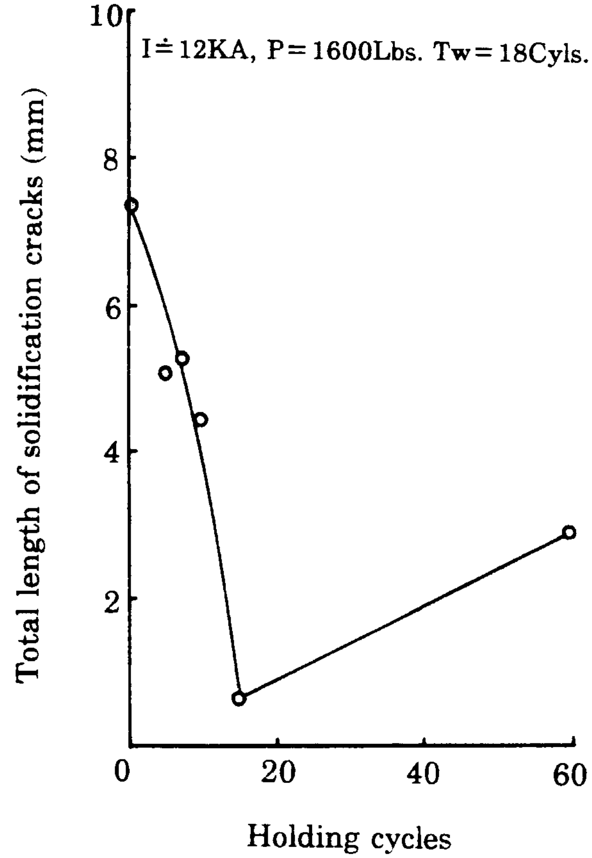

Fig. 3 Variation in crack length behavior with hold time.

Table 2 Tensile properties of test steel

Yield strength	80 ksi
Ultimate tensile strength	90 ksi

The spot welds were evaluated metallurgically and mechanically. Metallurgical characterization included optical microscopy and fracture analysis of failed shear tensile weld samples. Standard metallographic procedures were followed for sample preparation. The solidification structures were revealed using a picric acid plus sodium tridecylbenzene sulfonate etchant, and a 2% nital etchant was used to bring out the ferrite, martensite, and cementite microconstituents.

3. Results and Discussion

3.1 *Microstructural Characterization of the Weld Nugget*

The production of a weld nugget consists of two competing and simultaneously occurring reactions—melting and solidification. Because of the solute redistribution, both melting and solidification occur over a temperature range. Furthermore, despite the very rapid cooling rates common to the solidification of the weld nugget, it is still possible to observe differences in such rates within the nugget in view of the different solidification microstructures observed in the weld. However, it must be stated that the combination of mass and heat transfer is what influences such morphologies.

Figure 1 presents the cross section of a weld nugget made under conditions of no expulsion. Two solidification regions are noticeable; one is the cellular structure near the fusion line in the weld nugget. This appears as a rim around the nugget, as shown in the micrograph (Fig. 1). The other solidification structure, the most prominent, is columnar dendritic. The cellular solidification microstructure is the product of a limited constitutional undercooling caused primarily by the steep cooling rate at this location. A large constitutional undercooling is what leads to the extensive dendritic columnar solidification region.

Another typical characteristic of the weld nugget is the presence of solidification cracks, even when no expulsion occurs. This effect is a consequence of the fast cooling rates coupled with solute and impurity segregation during solidification. Most of this cracking is found between the dendrite arms, as shown in Fig. 2, but cracking at the faying surface may also be found. In correlating the effect of welding process parameters

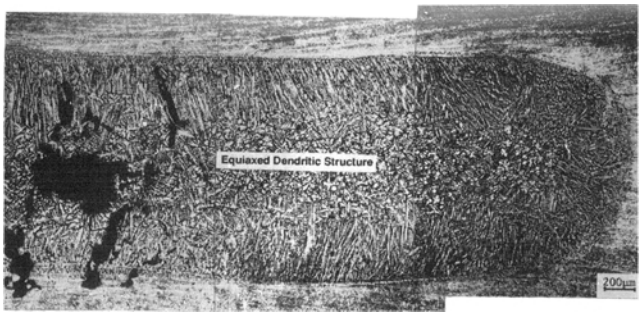

Fig. 4 Cross section of a spot weld made under expulsion, which reveals the equiaxed dendritic structure around faying surface.

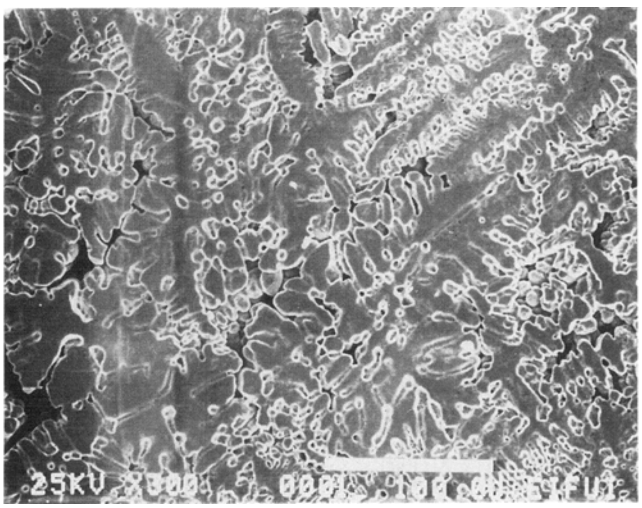

Fig. 5 Significant boundary cracks observed within the equiaxed dendritic structure.

on solidification cracking, it was found that holding time (i.e., the time that the water-cooled electrodes are left in contact with the spot welds after the flow of current is stopped) is an important parameter. Figure 3 shows the change in the amount of solidification cracking as a function of holding time for a fixed weld time and current. It was noted that, by reducing the holding time from 60 to 15 cycles, the total amount of cracking decreased. However, when this time was reduced below 15 cycles, cracking again became more pronounced, primarily near the faying surface. This last cracking event at the faying surface is most probably due to the fact that the electrodes were withdrawn before the nugget was completely solid, thus relaxing the compressive stresses at this location. This places the partially solidified region under tensile stresses, which combined with the contraction stresses lead to cracking.

Metallographic examination of weld nuggets with expulsion reveals the presence of another solidification microconstituent, equiaxed dendrites, as shown in Fig. 4. There is usually extensive solidification cracking in the nuggets of spot welds that experience expulsion; cracking is found between primary and secondary dendritic arms of the equiaxed structure, as

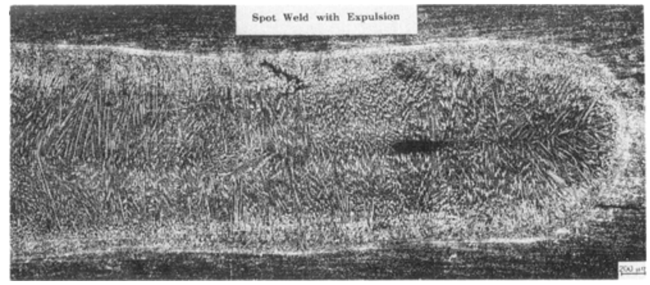

Fig. 6 Spot weld with expulsion showing a double image rim around the nugget.

shown in Fig. 5. Another feature observed in spot welds with expulsion was the presence of a "double image" rim surrounding the weld nugget, as noted in Fig. 6. The occurrence of these two microstructural features, i.e., the equiaxed dendritic structure and the double image rim, is apparently the result of an interrupted solidification process. That is, during the weld time cycle, as the liquid weld nugget increases in size, a critical time is reached, where the liquid metal escapes from the regular nugget containment. This results in the formation of a cavity about the center of the nugget, which causes an interruption of the current flow. This current attenuation was detected in Wu's early investigation.[9] Immediately, the liquid zones closer to the water-cooled copper electrodes begin to solidify in the absence of a continuous heat supply; however, this solidification is suddenly stopped as soon as the surface material in contact with the electrodes is indented, due to the applied electrode load, thus closing the cavity inside the molten weld nugget and allowing the resumption of the welding current, leading to the second heating process. Because of the turbulence accompanying the expulsion, some of the dendrite arms from the initial solidification process break loose, providing the nucleation sites for the equiaxed dendritic structure. The double image rim, as indicated earlier, is the result of the initial interrupted solidification and the formation of a second fine cellular zone during the second solidification, following expulsion and after the end of the weld time.

3.2 *Mechanical Evaluation of the Spot Welds*

The strength of the spot welds was evaluated by submitting them to a shear tensile test. These results were correlated with the welding process parameters and the soundness of the weld nugget. Figures 7 and 8 show that weld strength increases with an increase in weld current and weld time; this is expected in view of the fact that a larger weld nugget would develop with a higher weld current or a longer weld time, as shown in Fig. 9 and 10.

The increase in strength in terms of current and or weld time reaches a maximum, but then decreases with the occurrence of expulsion (Fig. 7 and 8), in spite of the increase in diameter in these spot welds (Fig. 9 and 10). Such a decrease in shear strength with expulsion is well known. Some of the failed tensile specimens that fractured along the faying surface were examined for spot welds with and without expulsion, as shown in

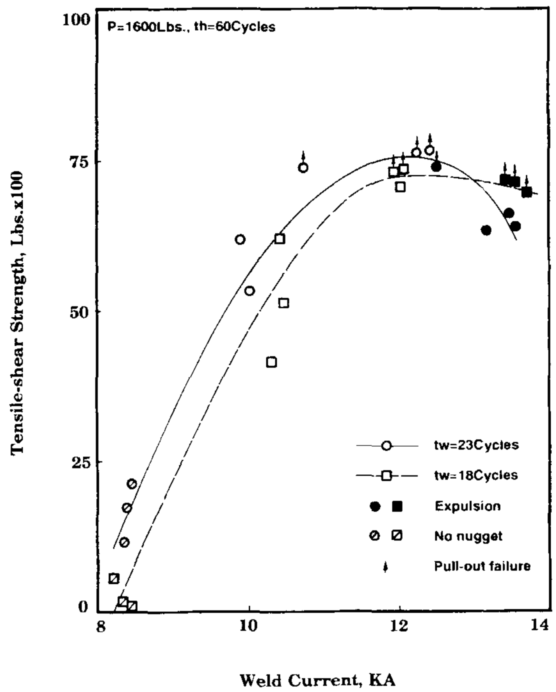

Fig. 7 Tensile-shear strength as a function of weld current when welding with two current levels, 10 and 12 kA, respectively.

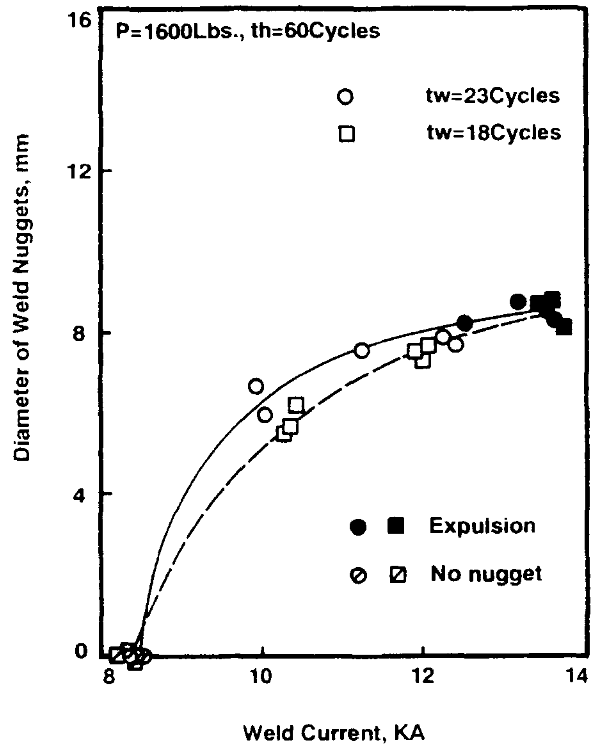

Fig. 9 Weld nugget size as a function of weld current.

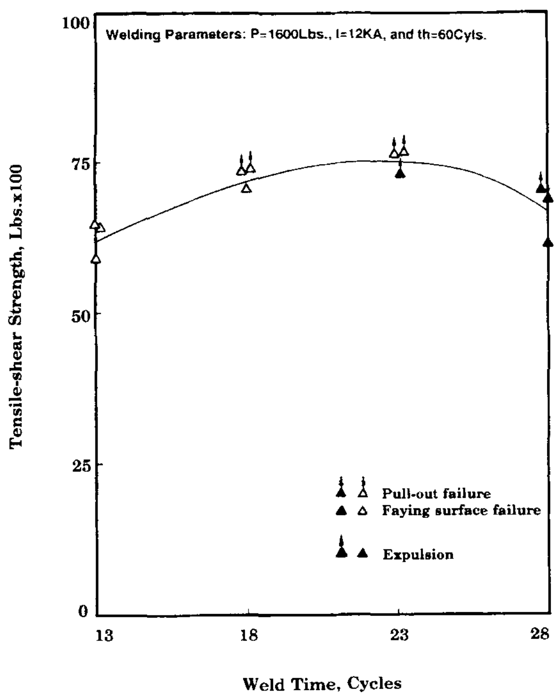

Fig. 8 Effect of weld time on the tensile-shear strength of sheet steel.

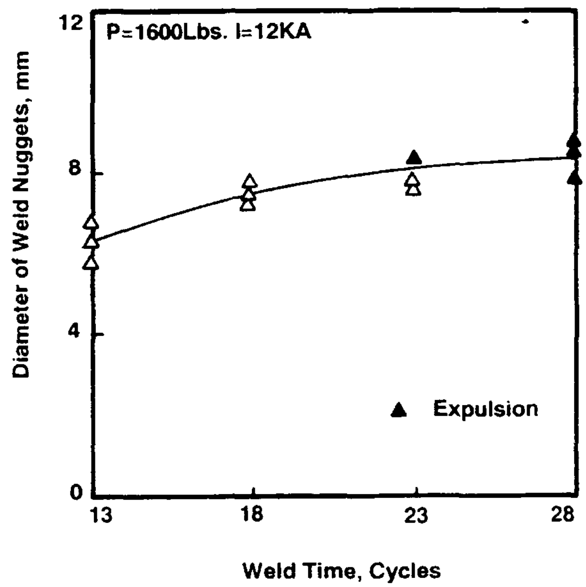

Fig. 10 Weld nugget size as a function of weld time.

the composite photos of Fig. 11 and 12. Selected fractography was performed, and the spot welds with expulsion were found to exhibit primarily a brittle quasicleavage fracture, with small regions of ductile dimple failure, in contrast to the mostly ductile and dimple-type fracture of the spot welds without expulsion. Of course, the difference in the cracking behavior is influenced by the presence of the equiaxed dendritic microstructure. Figure 13 consists of two photomicrographs from a tensile shear specimen corresponding to two areas in the same spot weld; note that the regions with the equiaxed dendrites exhibit no deformation associated with the crack, whereas other areas

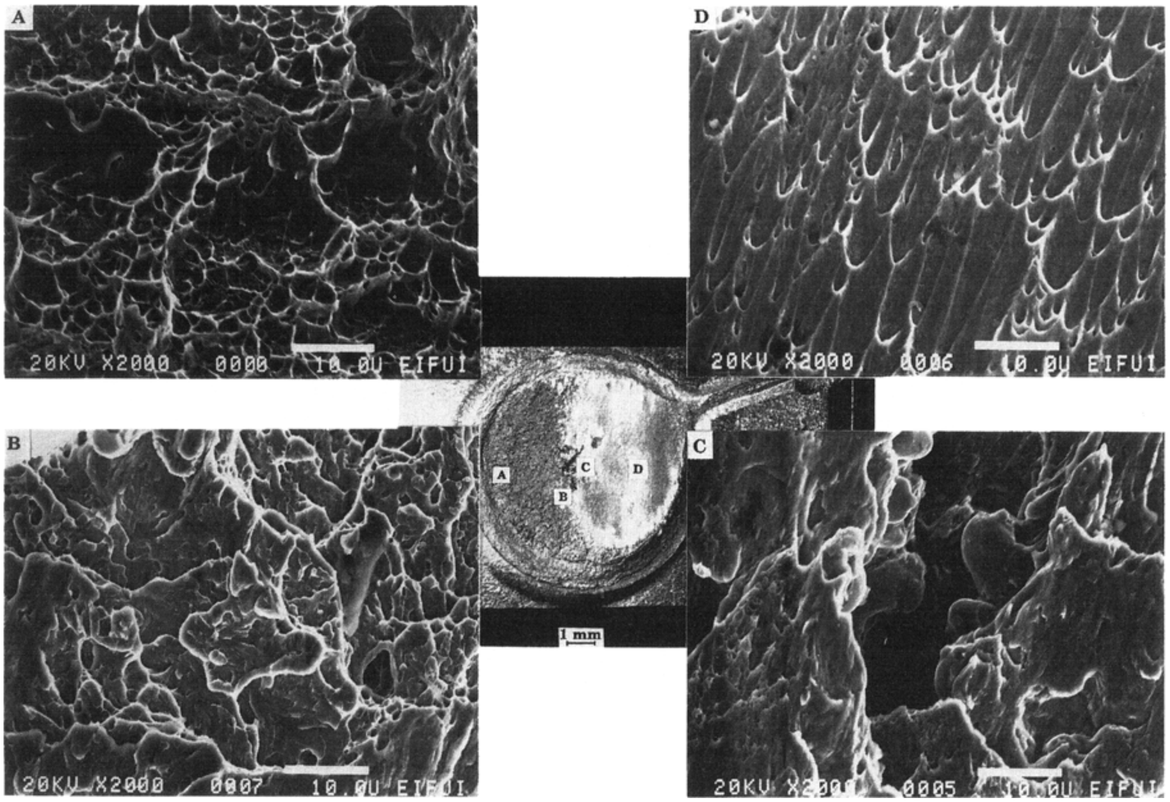

Fig. 11 Electron fractograph of a typical tensile-shear specimen with expulsion. (A) and (D) ductile dimpled fracture. (B) and (C) quasi-cleavage structure with boundary cracking.

with just the columnar dendrites exhibit deformation. Apparently, spot welds experiencing expulsion derive much of their strength from the presence of the tougher columnar dendritic structure, because the decrease in shear strength is not radically lower than that of a sound weld nugget. It is anticipated that a spot weld with expulsion would have a shorter fatigue life in view of the extensive cracking resulting from the solidification, as well as the presence of the equiaxed microstructure. However, a study[10] of very thin sheet steels (0.8 mm, or 0.03 in., in thickness) reported that spot welds produced with expulsion exhibited improved fatigue properties compared to those produced with similar parameters, but with no expulsion. Tests are presently underway to check the fatigue life of the material used in this investigation.

3.3 *Effect of Indentation on Spot Weld Strength*

Figures 7 and 8, which show that strength of the spot welds as a function of welding parameters, also indicate that weld failures occur along the faying surface of the weld nugget, as well as normal to the direction of the applied load. Such failures have been described as pull-out failures. Figure 14 illustrates this type of fracture, which can occur in the weld nugget or in the heat-affected zone (HAZ).

It was described earlier that expulsion is also manifested by a deep indentation at the external sheet surfaces in contact with the electrodes. Such indentation causes significant material flow and gross deformation within the sheet metal. The surface indentation as a function of welding time for a set of spot welds produced at 12 kA and with an electrode force of 1600 lb was measured and is plotted in Fig. 15. As expected, indentation increased continuously with weld time, at constant load, up to 18 cycles, where a sudden jump occurs in spot welds that have experienced expulsion. For this particular steel composition and thickness, an electrode force of 1600 lb, a weld time of 18 cycles, and a current of 12.0 kA are the critical settings for the occurrence of expulsion.

The effect of surface indentation on tensile shear strength of the spot weld could be explained by analyzing the development of internal stresses on the onset of expulsion. Figure 16 illustrates the different loading modes that occur when a spot weld specimen is submitted to a shear tensile test. Note that the portion of the HAZ just outside the weld nugget is just "forged together," but not bonded (Fig. 16b). In analyzing the onset of failure as a result of the shear tensile test, the "forged" portion could be considered the equivalent to a crack-like flaw, and the failure will commence at the crack tip. As the tensile shear load is applied, two interior stress components are generated at the tip, as shown in Fig. 16(b), which lead to two types of fracture modes, tensile and sliding modes. From the standpoint of fracture mechanics, the stresses in the vicinity of a crack tip may be described in terms of stress-intensity factors. During loading, when the stress-intensity factors exceed the critical intensity factors of the material, K_{Ic} or K_{IIc}, the crack tip is no longer sta-

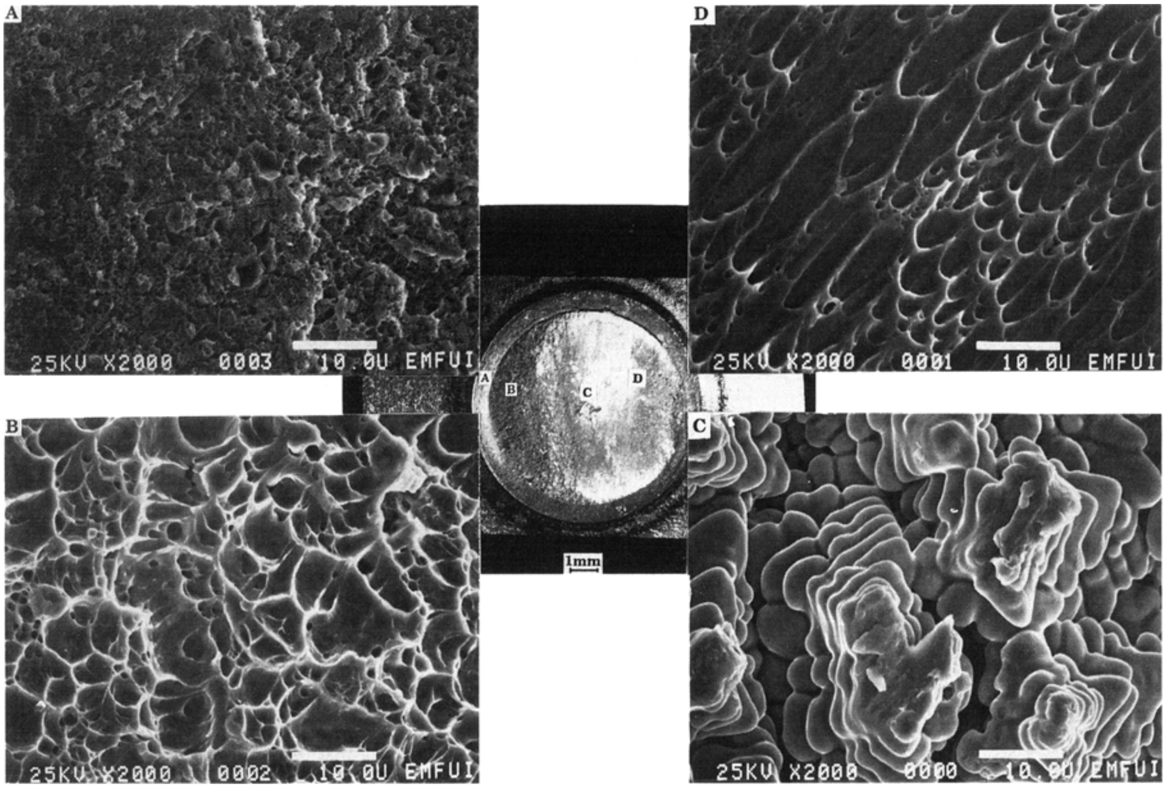

Fig. 12 Electron fractograph of a typical tensile-shear specimen with no expulsion. (A) edge bonding region. (B) and (D) microvoid coalescence (ductile dimpled fracture). (C) broken columnar dendrites.

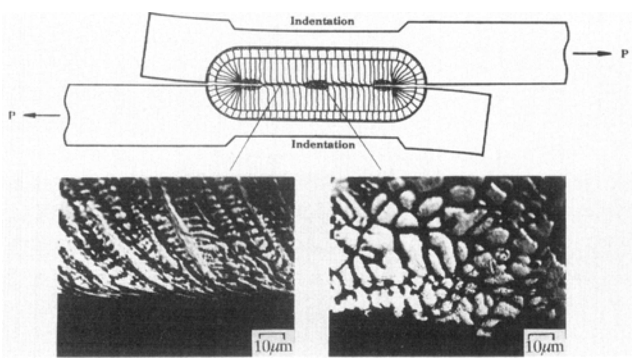

Fig. 13 Optical micrograph of an interface-failed specimen showing that the columnar dendritic structure becomes plastically deformed before fracture (A) compared to the brittle fracture of the equiaxed dendritic structure (B).

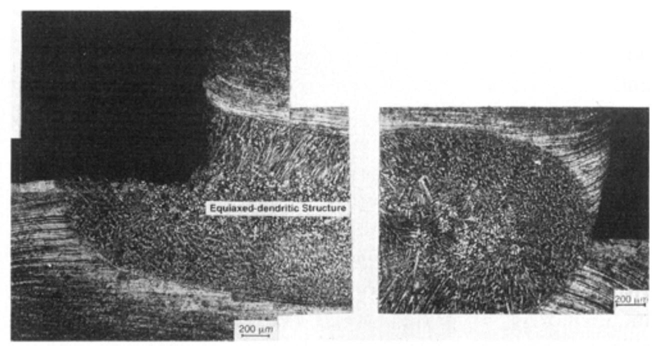

Fig. 14 Pull-out failure, apparently originated at the faying surface and partially propagated along this interface.

ble and fracture occurs. Kassir et al.,[11] in their study of external elliptical cracks in elastic solids, defined the stress-intensity factors K_t and K_s for tensile and sliding modes, for a single elliptical connection between half spaces:

$$K_t = \frac{\delta}{2}\sqrt{\pi a} \qquad [1]$$

and

$$K_s = \frac{\tau}{2}\sqrt{\pi a} \qquad [2]$$

where δ and τ are the normal and shear tensile stresses, respectively, acting at the crack tip, and a is the radius of the elliptical connection between half spaces. If one considers that a spot weld is made between sheets rather than half spaces, some approximations should be considered to analyze this case. The effect of finite thickness is to increase K_s to above the half space values and to introduce tensile mode displacements, leading to K_t values on the same order as K_s values.[12]

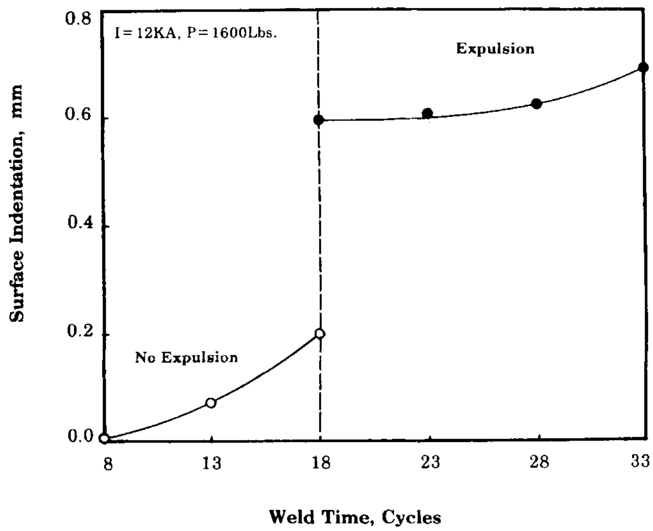

Fig. 15 Effect of weld time and expulsion on surface indentation.

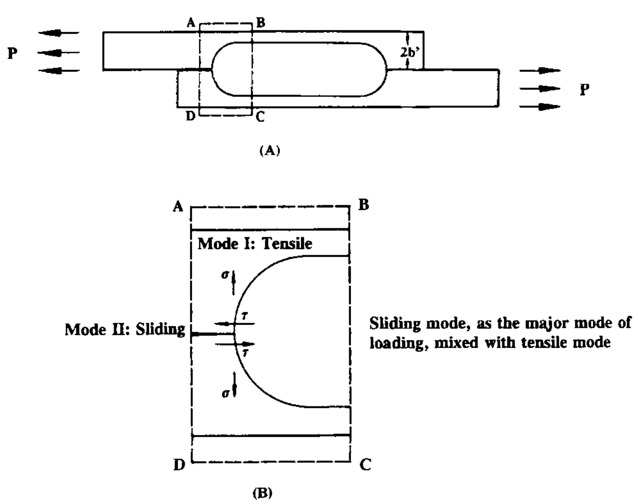

Fig. 16 Fracture modes involved in the failure process of spot welds under tensile-shear loading.

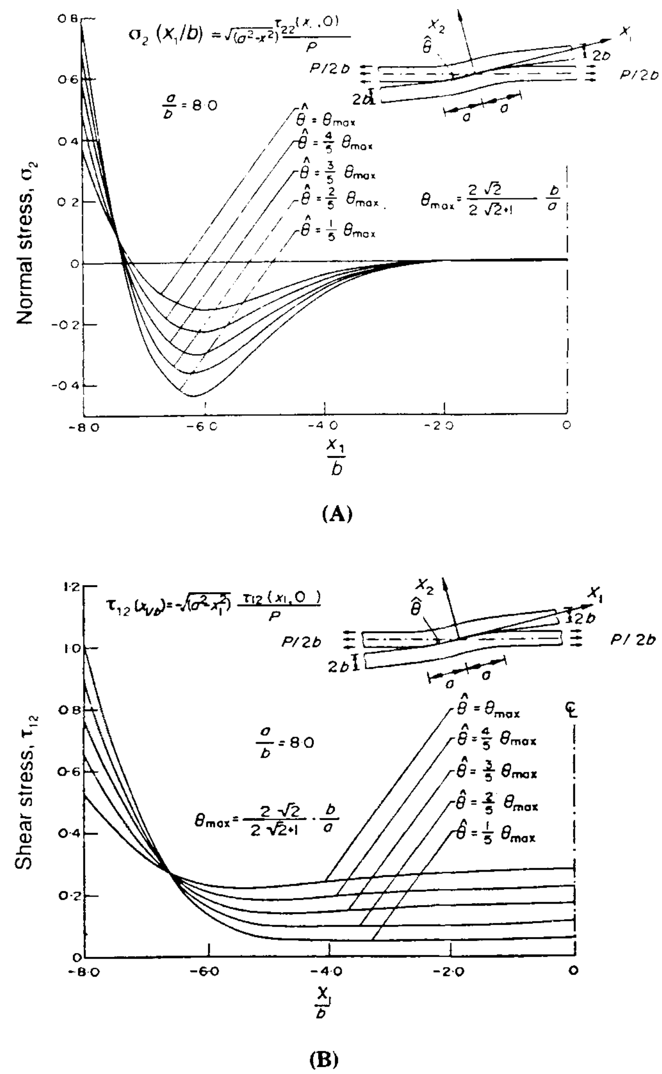

Fig. 17 Variations of normal stress (a) and shear stress (b), respectively, as a function of the joining area radius and sheet steel half thickness in an analogue analysis of adhesive lap joint under tension shear.

Reflecting on Eq 1 and 2, the larger the nugget size, the greater the K_t and K_s values. Thus, expulsion, which generally increases the nugget size, will cause an increase in these stress-intensity factors to a level that is greater than the toughness of the weldment causing fracture. The work of Pook on stress-intensity factors for spot and similar welds[12] correlates the stress-intensity factors for the tensile (K_I) and sliding (K_{II}) modes with the nugget size and thickness of the sheet material:

$$K_I = \tau(\pi a)^{1/2}\left[0.605\left(\frac{a}{b}\right)^{0.397}\right] \qquad [3]$$

$$K_{II} = \tau(\pi a)^{1/2}\left[0.5 + 0.287\left(\frac{a}{b}\right)^{0.710}\right] \qquad [4]$$

where K_I is the stress-intensity factor introduced in mode I of loading; K_{II} is the stress-intensity factor introduced in mode II of loading; τ is the average shear stress, which depends on the external load applied and can be affected by the internal stress state; a is the radius of the spot weld; and b is the half thickness of the sheet material.

Equations like 3 and 4 clearly illustrate the negative effect of expulsion by increasing the stress-intensity factors. The increase in nugget size and half thickness reduction due to indentation both contribute to greater values of K_I and K_{II}. As a result, K_{II} most probably will exceed K_{IIc}, causing fracture.

The model developed by Chang and Muki[13] of an adhesive lap joint under tension shear describes the stress distribution along the bonded interface as a function of the metal sheet half thickness and radius of the lap joint, as shown in Fig. 17. Considering that the weld nugget is comprised of a homogeneous martensitic microstructure, one can assume that qualitatively the stress distribution along the faying surface of a spot weld under tensile shear is similar to that shown in Fig. 17. Then, the increase in the nugget radius and decrease in the sheet steel half thickness due to expulsion and indentation would change the normal stresses at the edge of the nugget from a compressive to a tensile state (Fig. 17a). Similarly, the shear stresses would experience a significant increase in magnitude beyond a critical ratio of the nugget radius to sheet metal half thickness (Fig. 17b). This critical stress state coupled with the presence of a very brittle microstructure (martensite) and of localized structural inhomogeneities, e.g., a forged HAZ and a cast weld nugget structure, will weaken the joint, thus leading to fracture. The spot welds in Fig. 7 produced at about 13.5 kA for a welding time of 23 cycles all have expulsion and failed along the faying surface because of the solidification cracks and equiaxed dendritic structure at this location. On the other hand, the spot welds produced at about 12.0 kA for the same weld times experienced pull-out fractures; however, they had higher strengths. This is probably due to the presence of tougher microstructures in the HAZ away from the fusion line.

The pull-out fractures are failures under tension; apparently the reduction in the cross section as a result of indentation by the copper electrodes is a factor in weakening the weldment to the point that the load-carrying ability of the weldment is lower at the reduced cross section than at the faying surface of the weld nugget. Of course, other metallurgical defects, such as solidification cracks in the weld nugget and liquation cracks in the HAZ, cannot be neglected, particularly if these are located perpendicular to the applied load. Figure 14 shows that the pull-out failure began as a crack along the faying surface on the side where the expulsion occurred (Fig. 14a). However, in its propagation, the crack most probably ran into a solidification crack perpendicular to the applied stress that accelerated the failure of the weldment. Figure 14(b) shows the side opposite the expulsion end, and consequently, no liquid metal is expelled at this end. Note the absence of the faying surface crack; however, the pull-out fracture is readily observable, and it is located at the HAZ in the indented region.

4. Conclusions

Expulsion leads to the formation of an equiaxed dendritic solidification structure, located primarily along the faying surface. The equiaxed dendritic structure results from the segregation to the faying surface of fragments of dendrite arms formed early in the welding process, which broke up due to the turbulence of the metal expulsion. These fragments provide the nucleation sites for the equiaxed dendrites.

The equiaxed dendritic structure is also characterized by extensive cracking, which accelerates fracture along the faying surface under shear tensile loading, lowering the weld strength. Surface indentation is another characteristic of the spot welds that is aggravated with the occurrence of expulsion. It appears that such indentation contributes to pull-out failures.

Acknowledgments

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