Weld Nugget Development and Integrity in Resistance Spot Welding of High-Strength Cold-Rolled Sheet Steels

The relationship between sheet steel microstructure and welding cycles is investigated

BY Z. HAN, J. E. INDACOCHEA, C. H. CHEN AND S. BHAT

ABSTRACT. Spot welds were produced using a high-strength cold-rolled sheet steel 0.08-in. (1.9-mm) thick. The welding parameters were systematically varied to examine their effects on nugget formation, microstructure, and mechanical properties. Following welding, several spot welds were cross-sectioned and mechanically polished for metallographic examination. Other spot welds were submitted to shear tensile tests.

It is observed that welding current and weld time are more significant parameters than applied electrode force in affecting expulsion. In all the spot welds examined, it was found that solidification cracking could be reduced but not eliminated, and it was observed that for this particular steel, a weld cycle of 18 and a holding cycle of 15 resulted in the least amount of solidification cracking. Nugget displacement to one side of the faying surface, also known as "stuck weld," was observed in some samples that showed banding from rolling. Prior to melting, it appears that solid-state metallic bonding occurs during nugget development.

Introduction

Resistance spot welding is a joining process in which coalescence of the metal sheets is produced at the faying surface by the heat generated at the joint by the resistance of the work to the flow of electric current. This process has wide application in industries of mass production, where lengthy production runs and reliable conditions are maintained. The automotive industry is the major user, and it is also utilized by industries fabricating products with thin-gauge metals.

It is well known that high-strength cold-rolled sheet steels obtain their strength from a combination of fine grain size, solution strengthening and precipitation strengthening by means of microalloying additions of titanium, niobium and vanadium (Refs. 1, 2). Extensive studies, both by automotive and steel companies, have demonstrated that these steels can be easily formed into the desired shapes with only moderate changes in press-shop practice. In addition to their formability, it is imperative that these steels be weldable by resistance welding since this is the major manufacturing process used on automotive assembly lines for joining sheet steel parts together. Since low-carbon steel is readily spot welded, it is therefore the standard by which all other materials will be judged. It is reasonable to expect that the closer the welding characteristics of the high-strength cold-rolled sheet steels are to low-carbon steel, then the smaller the changes in accepted welding schedules.

The thermomechanical process of resistance spot welding is a complicated phenomenon which involves mechanical, electrical, thermal and metallurgical factors. These factors in combination with the welding parameters have a significant influence on weld nugget development and final geometry. In order to consistently produce sound weld nuggets, it is necessary to understand these complicated phenomena and evaluate the role of the major metallurgical factors and processing parameters.

Many high-strength steels are known to have narrow welding current ranges. Sometimes, this limited weldability is a consequence of the interfacial failure of the weld nugget (Ref. 3), producing an apparently smaller fusion zone. High-strength sheet steels have also been shown to be more susceptible to expulsion because of their higher electrical resistivity (Refs. 4–6), hence, lower welding currents must be used with the higher resistivities to avoid expulsion in spot weld production (Ref. 7). The physical variables of the metal may include not only the composition of the steels, but also the surface condition. Surface effects have been studied (Refs. 8, 9) and found to have noticeable effects on spot weldability. Likewise, chemistry varia-

KEY WORDS

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Z. HAN and J. E. INDACOCHEA are in the Civil Engineering, Mechanics and Metallurgy Dept., University of Illinois, Chicago. C. H. CHEN and S. BHAT are with Inland Steel Co. Research Laboratories, East Chicago, Ind.

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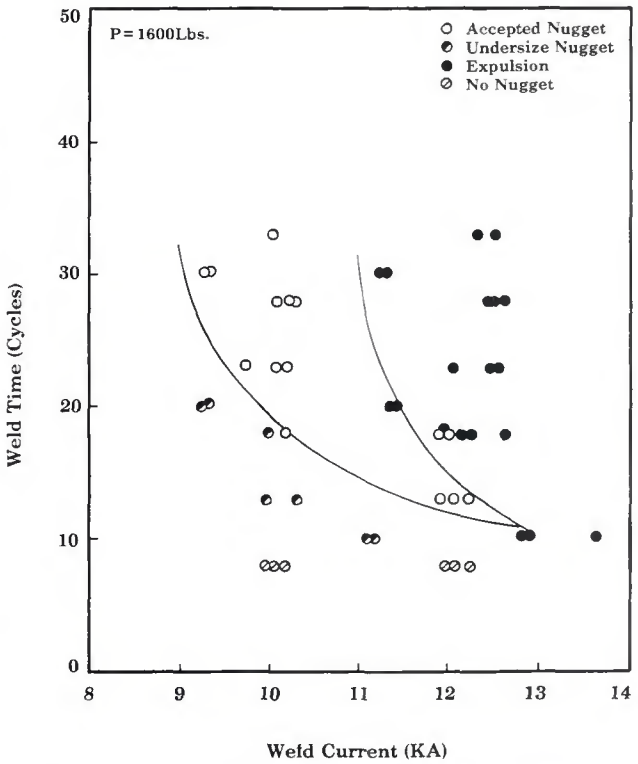

Fig. 1 — Lobe curve for the sheet steel used in this investigation.

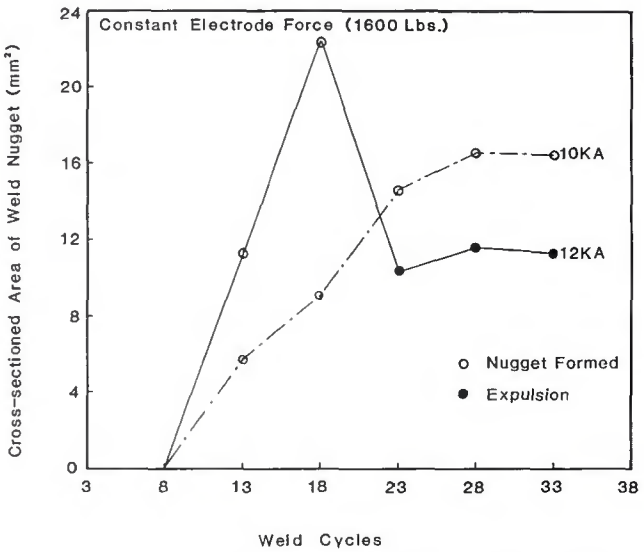

Fig. 2 — Weld nugget size as a function of welding time (cycles) for two welding currents.

tions have been found to have noticeable effects on spot weldability (Refs. 9–11).

The objective of this investigation is to assess the effect of processing characteristics and sheet steel microstructure on nugget development and integrity.

Experimental Procedure

Spot welds were produced using high-strength cold-rolled sheet steel coupons of dimensions 4 X 1 X 0.08 in. (102 X 25.4 X 1.93 mm). The steel composition and mechanical properties are shown in Tables 1 and 2. The steel coupons were used in the as-rolled condition and were cleaned thoroughly with acetone. Several spot welds were processed where one welding variable was methodically varied as the others were held fixed. A Sciaky press-type 100 kVA single-phase resistance welding machine was used. The electrodes utilized were a Class II copper alloy, of a composition of 99.2% Cu and 0.8% Cr. The tips had a contact diameter of 0.31 in (7.9 mm) and a 45-deg truncated cone nose in accordance to the manufacturing standards of the Ford Motor Co. (Ref. 12).

Following welding, the spot welds were cross-sectioned and mechanically polished for metallographic examination. A sodium trydecylbenzene sulfonate plus picric acid etchant was used to reveal the solidification structure, and 2% nital was used to bring out the phase microconstituents. A LECO 300 metallograph with an image analyzer was used for the microstructural evaluation.

Table 1 — Steel Composition, wt-%

C	Si	Mn	S	P	Al	N
0.12	0.27	1.42	0.003	0.023	0.053	0.010

Table 2 — Steel Tensile Properties

Yield Strength: 80 ksi
Ultimate Tensile Strength: 90 ksi
Elongation: 18%

Results and Discussion

Effect of Welding Parameters on Nugget Characteristics

In the continued desire to increase productivity, it has been demonstrated that the maximum welding speed that can be attained increases as the sheet thickness is reduced (Ref. 13). However, this increase in welding speed has to be compromised with the possibility of expulsion, which occurs at high currents (Ref. 14). This expulsion is a result of the excessive heating and of the molten and plastic deformation of the metal, next to the nugget, extending beyond the electrode contact zone which is inadequately forged. This phenomenon has generated concern among manufacturers because of the possible connection with lack of weld strength and rapid electrode deterioration (Ref. 15). This has led to the determination of operating ranges over which acceptable spot welds are obtained on plain carbon sheet steel.

A graphical representation of ranges of welding variables over which acceptable spot welds are formed on a specific material welded with a preselected electrode force is known as a "spot weld lobe curve" (Ref. 16). Characterization of such curves must be made if effective utilization of welding parameters is sought to consistently produce sound spot welds. The spot welds defining the lower limit of the lobe curve are small, and in some cases undersize, resulting in weaker nuggets. On the other hand, the spot welds at the upper limit of the curve are larger, and quite frequently, they experience expulsion, which decreases weld strength and increases electrode wear. Figure 1 shows the lobe curve developed for the steel used in this investigation.

The cross-section areas of the spot weld specimens used to construct the

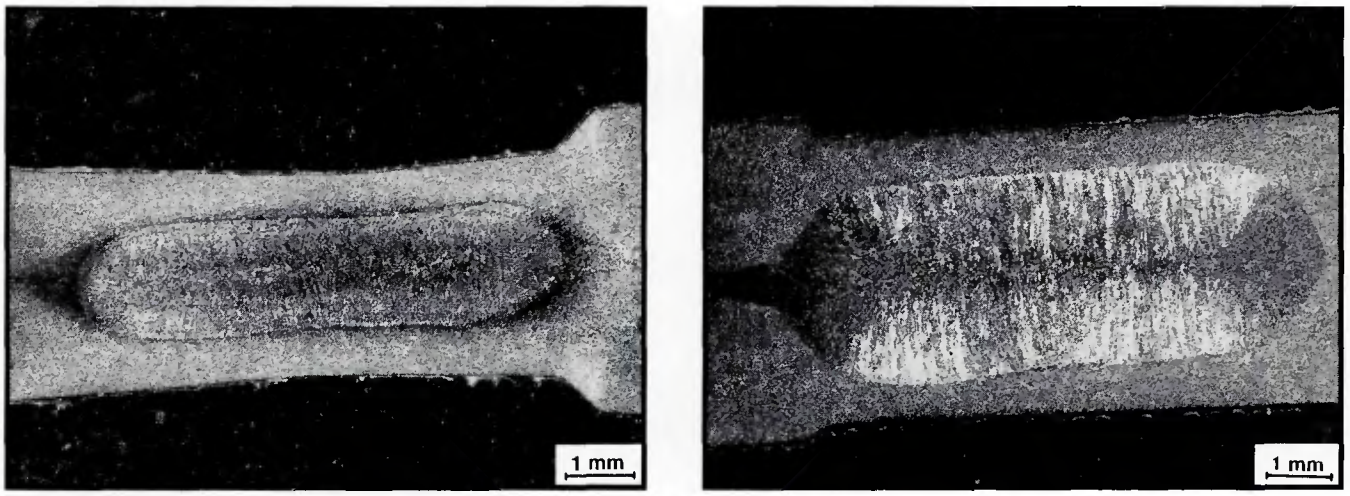

Fig. 3 — Cross-sectional versions of spot welds with (left) and without (right) expulsion.

been plotted as a function of the weld cycle in Fig. 2 for two welding currents (10 kA and 12 kA) at a constant electrode force of 1600 lb (727 kg). As expected, the tendency is for the nugget to increase in size with longer weld cycles up to a point, beyond which it may either remain constant or experience expulsion, causing the normal weld nugget to be thinner since the rest of the liquid weld metal is expelled beyond the usual nugget containment. The spot welds processed with a 10-kA welding current sustained a gradual increase in nugget size up to a weld cycle of 23. Note that the nugget size of the spot welds corresponding to weld times of 28 and 33 cycles remained constant and did not experience expulsion. The 12-kA spot welds increased in size at a faster rate, but experienced expulsion which resulted in a thinner nugget thickness as seen in Fig. 2. Figure 3 shows two typical spot welds corresponding to weld cycles of 18 and 23 for an applied current of about 12 kA. Note the occurrence of expulsion and deep indentation for the 23-cycle spot weld specimen. It is apparent that external indentation of the steel sheet is a consequence of nugget expulsion.

The effect of applied electrode force on nugget characteristics was monitored also in terms of nugget size and whether expulsion occurred, as shown in Fig. 4. The increase of electrode force is accompanied by a small but continuous reduction in nugget size, clearly observed for the 10-kA weld samples. This small decrease in the weld nugget cross-section area could be explained, in part, to be due to the fact that the increase in applied force would result in a minor decrease in the sheet thickness and in a larger increase in contact area at the faying surface in view of the deformation of the asperites. Both factors will contribute to a small reduction of the total resistance of the system, leading to a reduction in the amount of Joule heat. The 12-kA spot welds all showed expulsion, and no consistent relationship could be established between cross-section area size and applied electrode force. The weld time used for processing these last spot welds was 23 cycles. Note that previously it was determined that such weld time at 12 kA resulted in expulsion (Fig. 2). Examining the data presented in Fig. 4 for the same welding time and several applied electrode forces and for two welding currents, expulsion only occurred in those spot welds processed at the higher welding currents. Such results indicate that expulsion is not dependent only on the applied force. In the case of the 10-kA current, no expulsion was found even when the applied force was as low as 1400 lb (636 kg). On the other hand, for the spot welds produced at 12 kA, expulsion was found even in those welds produced at 2200 lb (1000 kg). It is apparent then, that the welding current and time are the most sensitive welding parameters to cause expulsion.

Weld Nugget Microstructure and Mechanical Properties

The microstructure of all these spot welds is martensitic and their solidification structure is influenced by the degree of constitutional undercooling. The solidification structure is cellular near the fusion line, followed by a columnar dendritic structure and equiaxed dendrites if expulsion occurs at the faying surface, as seen in Fig. 5. It was established that the microhardness difference between the cellular, columnar and equiaxed structures is more dependent on the amount of carbon available than on the magnitude of the cooling rates. The carbon content should be low for the cellular structure because solidification begins at this location and consequently the solute segregation is low. The martensite corresponding to the columnar dendrites would have a higher

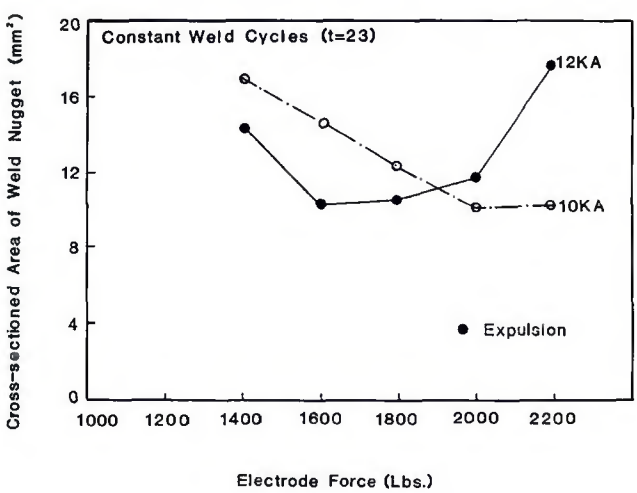

Fig. 4 — Effect of electrode force on nugget size for two applied currents.

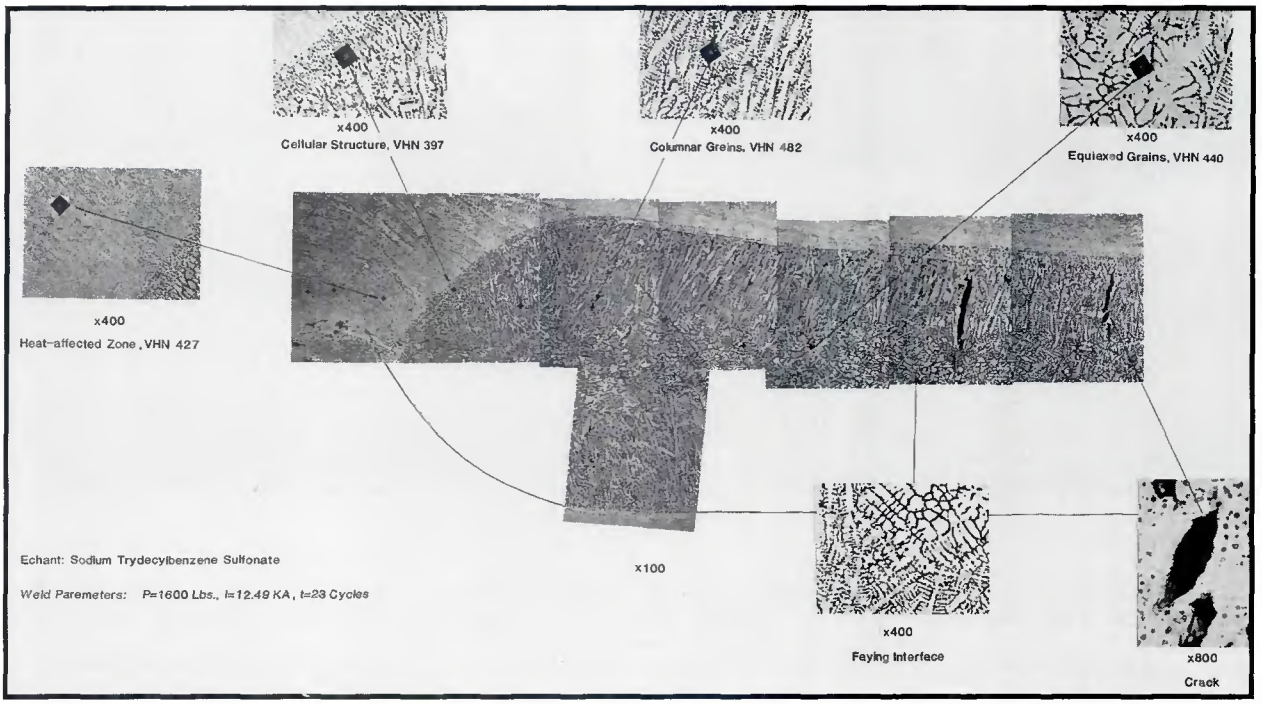

Fig. 5 — Solidification microstructures observed in a weld nugget of the high-strength cold-rolled sheet steel.

and a more uniform carbon distribution, because of the steady-state solidification. The highest microhardness was encountered in the equiaxed region, apparently, the result of the largest carbon segregation, which is expected in this region as a result of the overlapping of the opposite solidification fronts.

A defect frequently present in the weld nugget is solidification cracking. Several factors affect its occurrence, *e.g.*, impurity segregation, cooling rate and processing stresses. In this investigation, the effect of cooling rate on solidification cracking was studied by varying the holding cycle and by maintaining the weld current at 12 kA, the electrode force at 1600 lb, and the weld time at 18 cycles. Several spot weld macrographs corresponding to different holding cycles are shown in Fig. 6. It is observed that by decreasing the holding time from 60 to 15 cycles there was a decrease in the extent of solidification cracking. However, as the holding time was reduced below 15 cycles, there was again an increase in solidification cracking, at the faying surface, probably caused by the relaxation of the system (withdrawal of the electrodes) before a large portion of the liquid metal solidified. A relative measurement of the total crack length on these samples was performed and plotted as a function of holding cycles, as shown in Fig. 7. Note that the amount of solidification cracking for holding times lower than 15 cycles was greater than for the commonly used 60 cycles. Holding cycles lower than 15 apparently do not allow sufficient time for the weld nugget to solidify thoroughly before the electrodes are withdrawn, and consequently, cracking results upon release of the electrodes.

Tensile shear tests were performed on these spot weld samples to establish the effect of solidification cracks on shear strength. These results, presented in Fig. 8, show no change in tensile shear strength among the spot welds processed with holding times of 60 and 30 cycles. But, there was a slight drop in strength for the welds processed with holding times of less than 15 cycles, yet it was not significant enough to be correlated with the degree of solidification cracking. However, it was established that weld time was most influential of nugget strength as shown in Fig. 9. The tensile shear strength of the spot welds increased with weld time, consistent with an increase in nugget size, as shown in Fig. 2. Furthermore, the spot welds with expulsion show lower strengths, as expected, because of the smaller nuggets compared to the spot welds with no expulsion and due to the effect of indentation.

Despite the lack of correspondence between solidification cracking and spot weld shear strength, it would be expected that this type of cracking can have an impact on the soundness of the nugget under more dynamic testing,

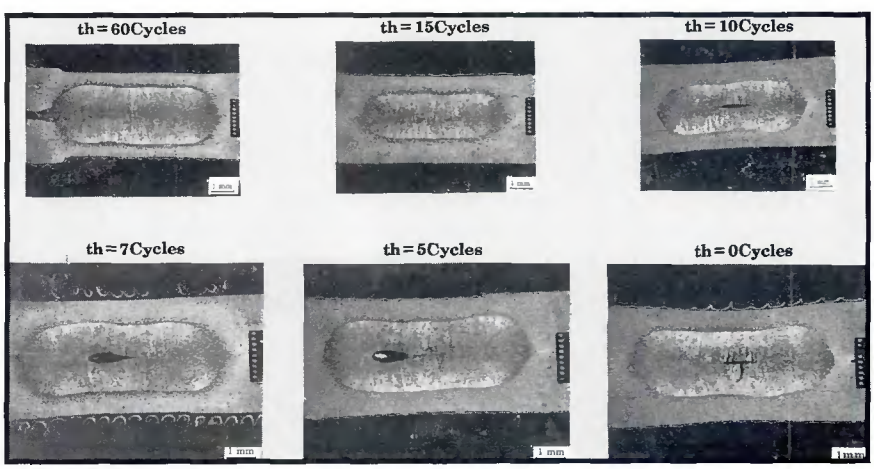

Fig. 6 — Effect of holding time on solidification cracking in spot welds.

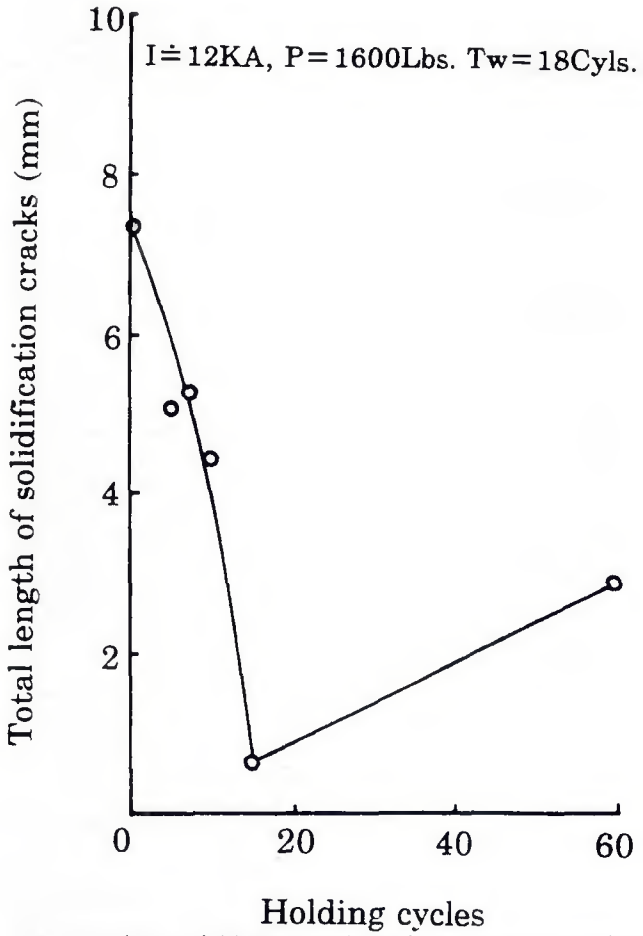

Fig. 7 — Relative solidification crack lengths in spot welds as a function of welding cycles.

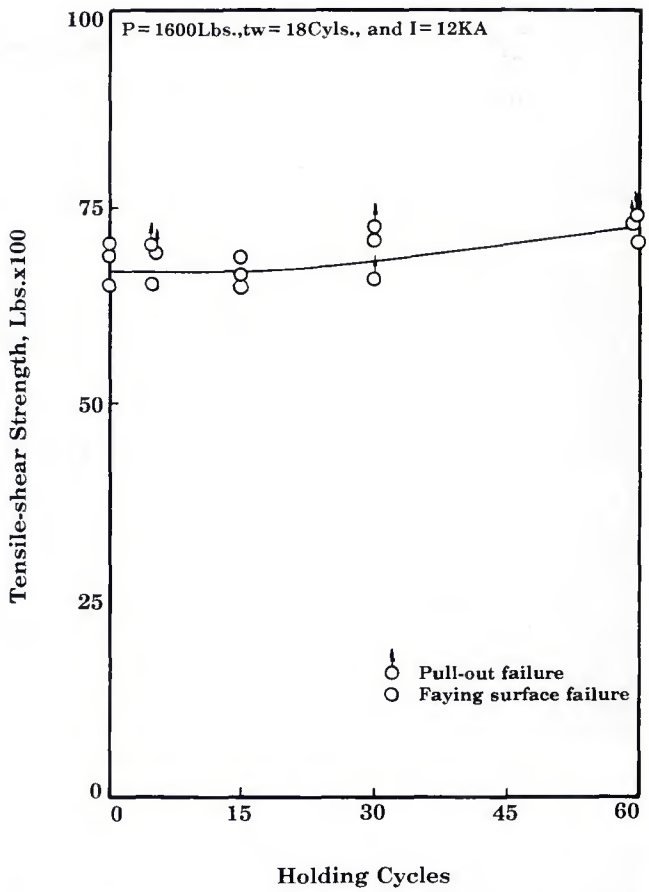

Fig. 8 — Effect of holding cycles on the tensile shear strength of spot welds.

such as fatigue. Fatigue tests will be conducted in the follow-up investigation.

Weld Nugget Displacement

In assessing the influence of resistance welding processing parameters on nugget characteristics, it was observed that, occasionally, the weld nugget was displaced to one side of the faying surface. This type of spot weld is sometimes known as "stuck weld" (Ref. 17), which is most frequently observed when welding sheet metals of dissimilar thicknesses.

Figure 10 shows several macrographs of weld nuggets arranged according to variations in weld time for two welding currents, and also as a function of current for a fixed weld time of 18 cycles. A constant electrode force of 1600 lb was used in producing these spot welds. It was observed for the series of spot welds processed with a 12-kA current that expulsion was eliminated and the nugget size increased when the weld time was reduced from 23 to 18 cycles. Further decrease of the weld time to 13 cycles, resulted in smaller nuggets be-

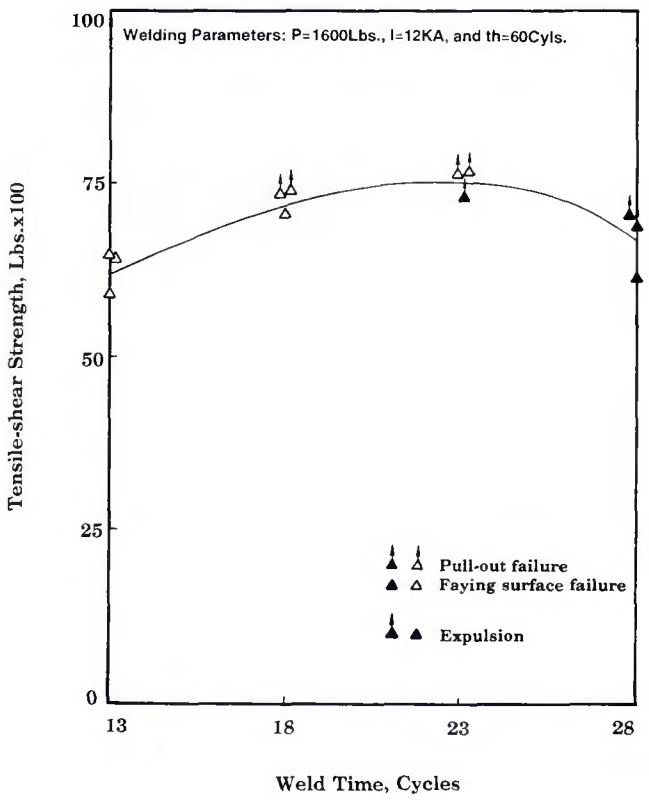

Fig. 9 — Effect of welding cycles on the tensile shear strength of spot welds.

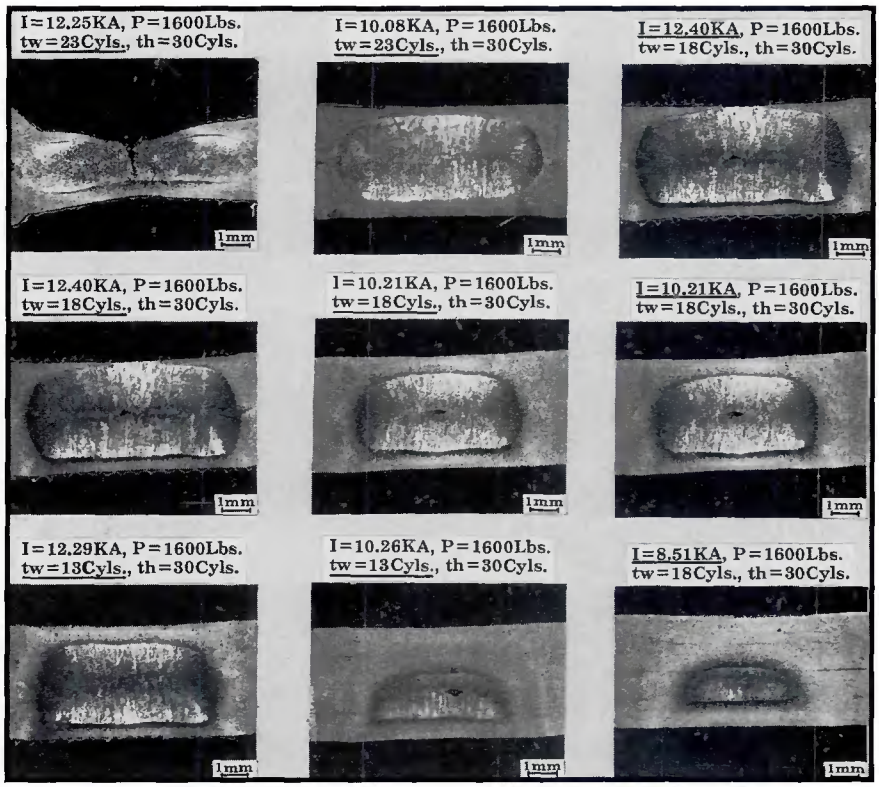

Fig. 10 — Effect of welding parameters on weld nugget soundness and appearance.

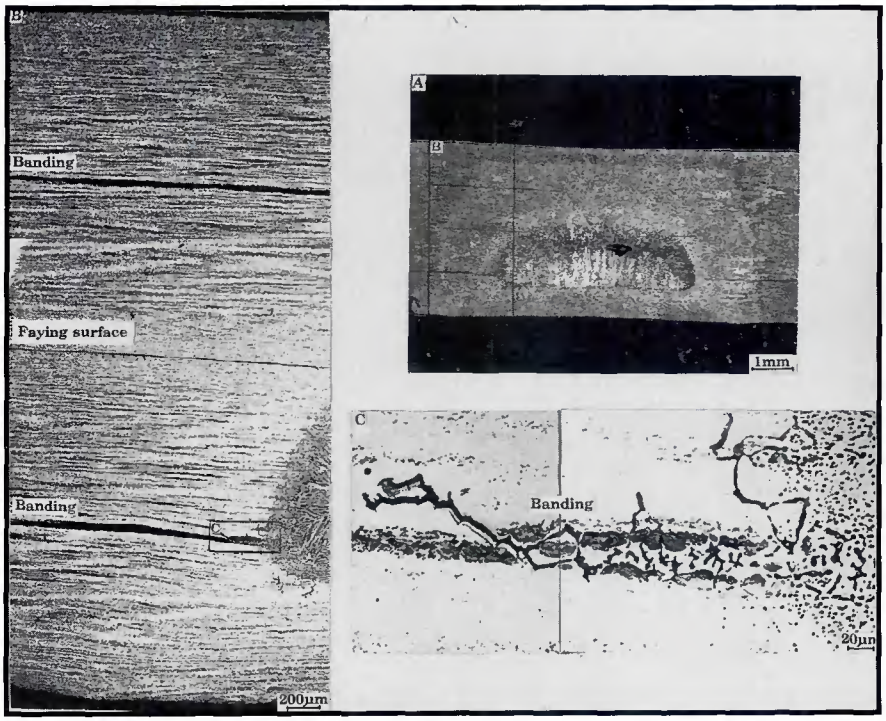

Fig. 11 — Micrograph composite showing "banding" in the sheet steel and the nugget displacement.

cause of the lower heat per time available due to the shorter current flow time. This same set of spot welds, however, showed no significant displacement of the weld nugget. In the case of the 10-kA spot welds, no expulsion occurred, and also, a decrease in nugget size accompanied the reduction of weld time. Most significant, though, was the shifting of the spot weld to one member of the steel sheets for the shortest weld cycle, as seen in Fig. 10. Similar results were found for the welds processed at the fixed weld time of 18 cycles and three weld currents. The greatest displacement of the weld nugget occurred for the lowest weld current of 8.5 kA.

In investigating the possible causes of nugget displacement, the sheet thicknesses were measured and found to be uniform in all cases. The copper electrodes were also examined for any possible irregularities that could affect the nugget formation, but were found to comply with specified dimensions, in accordance to the Ford Motor Co. manufacturing standards.

A microstructure feature observed in the base metal, "banding" shown in Figs. 11 and 12, is speculated to contribute to the nugget displacement. Resistivity is an intrinsic material characteristic which depends on the composition and microstructure of the material. The resistivity of a metallic conductor is known to increase with the concentration of a solute. Banding, on the other hand, includes not only solute segregation, but also pearlite lamination, both of which can disrupt the continuity of the ferrite and consequently increase its resistivity. Melting would then occur at a banding region if the resistance at this location is larger than that at the faying surface.

Figure 11 shows a displaced weld nugget cross-section that includes banding in the base metal. Note that banding is observed on both steel sheets of the spot weld, and the microstructural gap that this banding causes seems to be wider than the gap found at the faying surface. The nugget is displaced toward the bottom sheet steel, because apparently this microstructural irregularity ran continuously across the portion of the material compressed between the copper electrodes. The top steel sheet also shows banding, but this does not run all the way across the material squeezed between the electrodes.

A second possibility for the nugget displacement might be the presence of low-melting-temperature compounds such as iron sulfide and manganese sulfide with the banding microstructure. These compounds have melting points well below the melting temperature of iron, thus, despite the temperature at the

faying surface being several degrees higher, melting will commence at these binding regions because the local temperatures are already above the melting points of such compounds.

Figure 12 shows the weld nugget centered at the faying surface, despite extensive banding on the two sheet members; however, no banding lines were found running continuously across the material between the copper electrodes.

Formation of the Weld Nugget

The electrode force produces a local deformation at the common interface to seat the workpiece properly and to establish good electrical contact before current flows. This local deformation at the faying surface mechanically breaks down the surface films, oxides and asperites. It is understood that, during the welding cycle, the electrode load also helps to maintain proper electrical contact. The contact areas at the faying surface are dependent on the stress distribution and local deformation, thus, regions exposed to the largest stresses would be in tighter contact since the asperite gaps become reduced resulting in lower resistances. As the current starts flowing, the temperature at the faying surface increases causing further deformation and greater contact that could lead to solid-state bonding in some places. It should be noted that the current distribution at the faying surface is not uniform, since it also depends on the electrode geometry.

Figure 13 shows the state of the faying surface prior to any melting. Regions B and D clearly show metallic bonding in these areas without melting taking place, while region C shows a gap. It is apparent that with time melting will initiate at the center and will spread outward. These results, shown in Fig. 13 are consistent with a nonuniform but symmetrical stress distribution. Neid (Ref. 18) determined the stress distribution at the faying surface for a truncated electrode, similar to the electrode used in this investigation, where the stresses are highest at the regions corresponding to the edge of the electrodes and lowest at the center. Furthermore, because of the electrode geometry, the current flow lines would be more constricted near the edges, implying larger current densities at these edge locations than at the center of the electrode, as schematically represented in Fig. 14.

Based on the combination of these two factors, it could be speculated that, at the onset of welding, heat would be produced at a faster rate at the edges of the forming nugget, and because of the higher stresses at these locations, deformation will occur more rapidly, leading to solid-state bonding. As a result of this bonding, the contact resistance drops to zero at the edges, but a minor gap or high-resistance interface still remains at the center of the faying surface which does not completely stop the current flow. Melting could then initiate at this center spot and expand outward to the edges.

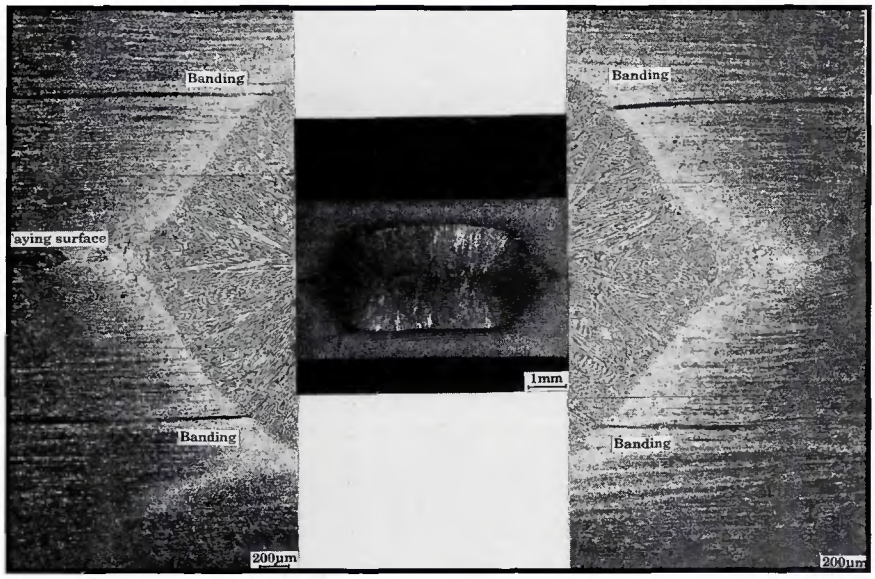

Fig. 12 — Banding in the sheet steel with nugget centered at faying surface.

Conclusions

1) In addition to composition and surface condition, the microstructure of the steel is an important physical variable in resistance spot welding.

2) Welding current and welding time are the most sensitive parameters to control expulsion. Tighter control of either parameter will improve weld nugget soundness and reduce expulsion, and thus improve electrode wear.

3) Holding cycles influence the extent of solidification cracking. In this study, it was found that holding cycles smaller or greater than 15 produced weld nuggets with larger amounts of solidification cracks. Despite the small changes in room-temperature tensile shear strength found in this study, it is expected that fatigue and toughness will

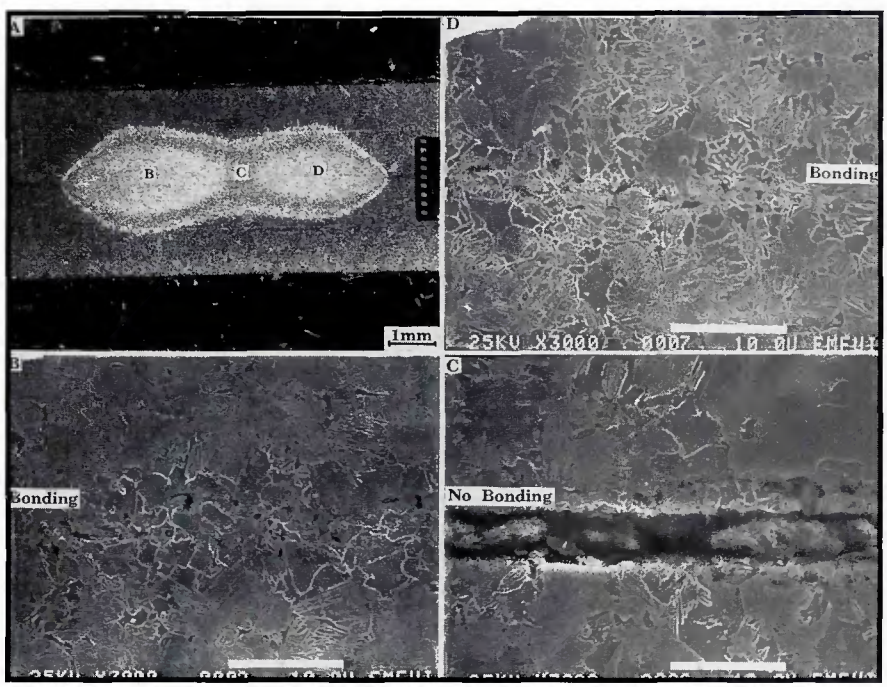

Fig. 13 — Microstructural characterization of different regions of the faying surface prior to the formation of the weld nugget.

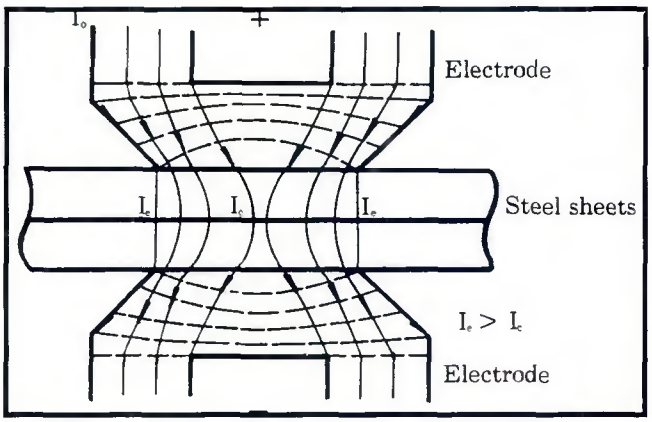

Fig. 14 — Schematic representation of the current distribution between electrodes.

be affected by the amount of this type of cracking.

4) It appears that solid-state bonding at the edge of the contact surface, followed by melting at the center are the first steps in nugget development.

Acknowledgments

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WRC Bulletin 369
December 1991

Nitrogen in Arc Welding — A Review

By IIW Commission II

In 1983, Commission II of the International Institute of Welding (IIW) initiated an effort to review and examine the role of nitrogen in steel weld metals. The objective was to compile in one source, for future reference, the available information on how nitrogen enters weld metals produced by various arc welding processes, what forms it takes in these welds, and how it affects weld metal properties.

This bulletin contains 13 reports and several hundred references related to Nitrogen in Weld Metals that has been prepared as a review to show the importance nitrogen has in determining weld metal properties.

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