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A High Speed Photographic Analysis of Spot Welding Galvanized Steel

High speed photography is a useful tool in analyzing the processes that occur over a short period of time. The technique reveals (and records for future study) the detailed step-by-step progress of spot welding in a three stage process

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ABSTRACT. This investigation used high speed photography to analyze qualitatively the sequential chain of processes that occur when a spot weld is made in galvanized steel and compared these processes with those observed in uncoated steels. A composite film of this study is available.

Analysis of films of spot welding galvanized steel established a three-stage process that included: (1) melting and displacement of the zinc coating from the weld zone and electrode-workpiece interface which required the first 4 or 5 cycles of the current, (2) internal heating of the steel for approximately 3 cycles of current during which the only observed phenomenon was the growth of heat zones, and (3) the growth and liquification of the steel weld nugget during the remaining 5 or 6 cycles of current. Comparative studies of uncoated steel exhibited only the second and third stages of this process which gave visual evidence of the necessity of longer weld times for coated steels.

Films of spot welding galvanized steel with electrodes in various stages of deterioration showed an increasing accumulation of material on the electrode edges which would partially melt during the weld. In addition, at later stages, larger cavities or pits formed in the electrode surface which filled with molten zinc during the weld. This material remained molten until after the weld current ceased. These results substantiated the mechanism of a compositional change in the tip of an electrode caused by continuous contact with molten zinc.

Spot Welding Characteristics of Coated Materials

Coated sheet steels have many applications due to their enhanced corrosion resistance. Steel with the common corrosion resistant coating of zinc is known as galvanized steel. Galvanized parts may be joined by spot welding. The automotive industry uses this process extensively.

One drawback to spot welding galvanized steel is the decrease in useful electrode life caused by the zinc coating. Use of electrodes with the proper geometry and composition can reduce but not eliminate the adverse effects of the zinc. Dispersion hardened alloys of copper, which use chromium or zirconium (both RWMA Class 2) as the alloying elements, are recommended for galvanized applications.[2, 3] The copper-chromium alloy is also recommended for uncoated steel.[3] A truncated cone has been found to be the best geometry conceived for spot welding galvanized steel.[2] Either the truncated cone or a spherical tip geometry may be used for uncoated steel.

The optimum welding schedule for galvanized steel has been the subject of extensive research. When welding galvanized steel, all welding parameters (especially the weld time) have to be increased over those used for plain steel. Most of the recommended schedules for galvanized steel indicate a 7% increase in current is required.[5] This higher current is needed to counter the effective decrease in heat generation resulting from the decreased resistance of the two zinc coatings at the faying surface. Furthermore, a 10% increase in electrode force is required to prevent expulsion of molten steel caused by thermal expansion in the weld. And finally, the greatest change required is a 25% increase in the weld time which is necessary to allow time for the displacement of the zinc from the weld zone.[2, 5]

Mechanisms of Electrode Deterioration

Several theories on the mechanism of accelerated electrode failure when welding galvanized steel have been published. All of these analyses start from the fact that a minimum current density is required to form a nugget of sufficient size. Any process that alters the contact area of the electrodes with the workpieces will in turn alter the current density. This electrode deterioration (i.e., change of shape or effective contact area) will ultimately cause the current density at the faying

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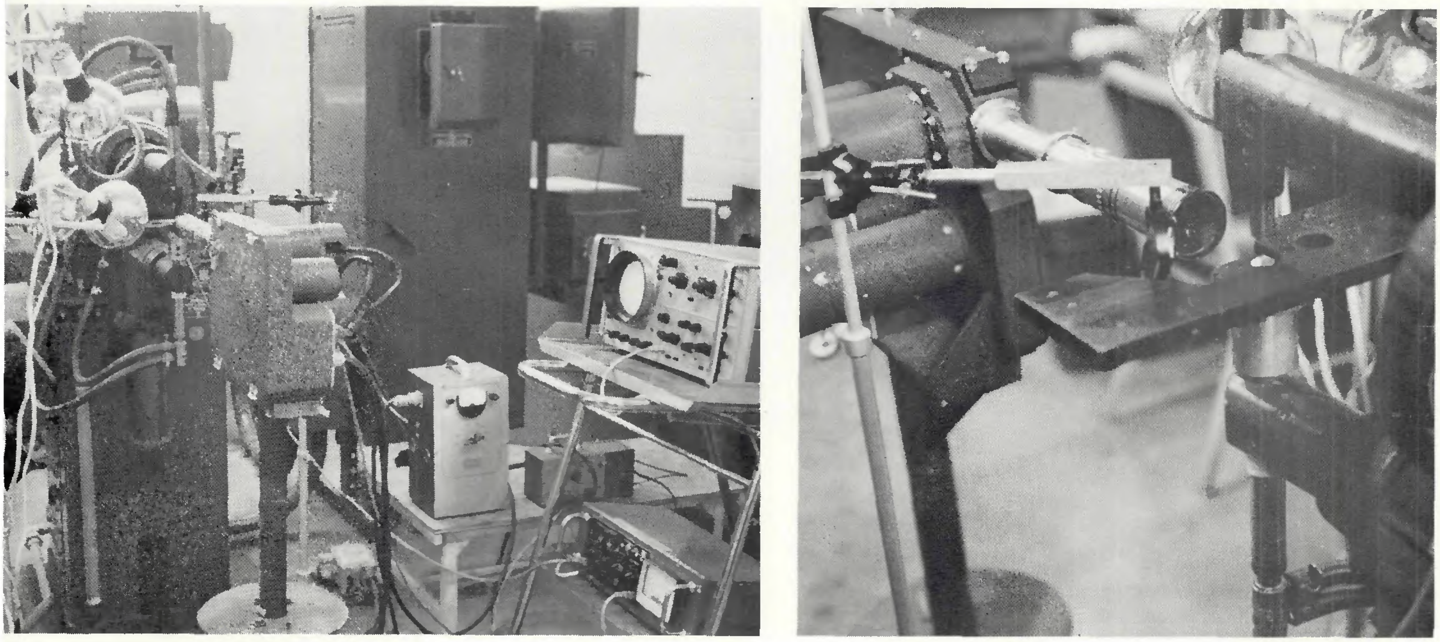

Fig. 1—Experimental equipment

surfaces to be so low that no nugget is formed.

The contact area of the electrode can theoretically be altered in three general ways when welding galvanized steel: (1) The electrode tip is plastically deformed by the welding process increasing its contact area, thus becoming a more efficient heat sink. This is the process that is normally responsible for ultimate electrode failure in welding uncoated steel. (2) The molten zinc at the electrode-workpiece interface tends to adhere to the corners of the electrodes, thus increasing the contact area. In later stages, the electrodes become severely pitted due to the alternate sticking and remelting of the zinc. (3) The electrode-workpiece interface is at a sufficiently high temperature for the copper to dissolve into the zinc and for the zinc to form a zinc-rich alloy on the tip of the electrode which melts and is partially discharged on subsequent welds. A quantitative chemical analysis of the electrodes by Howe gives support to the third mechanism.[4]

Purpose and Goals

This project was initiated to study spot welding of galvanized steel by examination of high speed motion pictures. The primary goal was to determine which if any of the proposed mechanisms of electrode failure was compatible with the detailed observation of the welding process. Plastic deformation of the electrodes should be observable in the films, if it exists, to lend support to the first mechanism previously described. The alternate sticking and remelting of the zinc at the electrode corners as proposed by the second mechanism should also be visible on film. If a molten zinc puddle could be shown to exist at the electrode-workpiece interface for a significant amount of time, then support would be given to the third mechanism of electrode deterioration. It was also hoped that visual proof of the need to increase the welding parameters for galvanized steel would also be obtained. A photographic analysis of plain sheet steel was made for comparison purposes and a composite film presenting the results of this study was planned as a culmination of the project.

High speed photography has been a successful technique previously used to study both projection and seam welding.[6, 7, 9] It is therefore reasoned that it should also give fruitful results when applied to spot welding.

Objective

The object of the experimental procedure was to produce a spot weld which could be photographed with a high speed motion picture camera. Close-up macroscopic photography was required since the weld being photographed was approximately 0.25 in. wide and the zinc coating on the specimens was no more than a few thousandths of an inch thick. An additional requirement was that, to the extent possible, the weld be analogous to a production weld. The experimental equipment was arranged as shown in Figs. 1 and 2.

Welding Equipment and Procedure

The spot welder used in this investigation was a standard air-operated rocker arm type machine of a 75 KVA rating. It was manufactured by the Acme Electric Welder Company with the following nameplate data: Type 3-18-75; Style, SOAR; Volts, 220; Cycles, 60; Primary Amp, 341; 75KVA Serial Number 2390.

The weld time and percent heat (secondary current) were controlled by a General Electric thyratron spot welding control. A General Electric sequence welding control set the squeeze time and hold time. These time duration controls could be set at any value from 0 to 60 cycles. The percent heat could be varied from 0 to 100%. Secondary current in the electrodes could also be adjusted by changing transformer tap positions.

The current and electrode force were measured for particular welder settings and are recorded in Tables 1 and 2. Secondary current was measured by a BWRA integrator and calibration unit which used the voltage induced in a specially wound pick-up toroid as the input to the integrator. A Hewlett-Packard Model 141-A variable persistence oscilloscope displayed the output signal of the integrator unit. The trace height could then be used to determine the root-mean-square current as shown in the following equation:

$$I_{RMS} = \frac{H_{p\text{-}p}TS}{G} = 5240\ H_{p\text{-}p}$$

where $H_{p\text{-}p}$ = peak-to-peak trace height in cm

T = toroid constant = $\dfrac{2620 \text{ amp}}{\text{volt}}$

S = Integrator scale factor = 10

G = gain of oscilloscope = $\frac{5\text{ cm}}{\text{volt}}$

A force gauge that utilized a dial indicator calibrated in pounds to measure the deflection of a steel U-member measured the force that the electrodes exerted on the workpieces. The indicatior was calibrated in 10 pounds per division.

Since the weld had to be located on the specimen so that it could be photographed with a high speed motion picture camera, special workpiece and electrode configurations were required. Samples were cut from 20 gauge (0.036 in.) 1008 cold rolled steel, hot dipped galvanized with a standard commercial coating weight of 1.25 oz/sq ft. The samples were rectangular, 1 in. by 2 in. A number of these specimens were clamped together and metallographically polished on one edge. Three grades of silicon carbide grinding paper, 320, 400, and 600, were used for wet grinding, followed by polishing with levigated alumina (15 micron) and Linde A (0.3 micron) powder on wheels. The samples were finally cleaned with trichloroethane spray-on solvent. Prior to welding, a pair of samples were taped together on the ends to facilitate alignment. The same procedure was used to prepare samples of 1008 cold rolled uncoated steel 0.048 in. thick. These samples were then rolled down to a thickness of 0.040 in.

Standard spot welding electrodes were modified to produce a weld on the edge of the specimens that could be photographed. RWMA Class 2 copper-zirconium flat tip electrodes of 0.625 in. diam (Mallory Part Number 4325) were machined to the dimensions shown in Fig. 3. Since the truncated cone geometry is generally considered to be the most satisfactory contour for spot welding galvanized steel, a similar geometry was selected for the photographic electrodes which had a rectangular cross section at the tip with the same total contact area as the normal electrode. It was believed that this configuration would give a reasonable facsimile of the welding process in the interior of the weld when the samples were aligned with the polished edge parallel and even with the edge of the electrode face. The faces of the electrodes were painted flat black prior to use to minimize glare in the photographs.

Welding schedules that closely approximated normal schedules were desired for the photographic analysis. The same weld time and electrode force were used. However, due to the rectangular shape of the electrodes, the current had to be increased to produce an adequate size weld. The nugget formed with the minimum current had an elliptical geometry. At a later stage in this study, the current was further increased to produce a fully molten nugget at the edge of the specimen. The schedule for plain sheet steel was determined experimentally and is listed in Table 3.

Welds made by this procedure were destructively tested by two methods to insure compatibility with a production weld. One method was a peel test on a tensile test machine in which like ends of the two workpieces were pulled apart. A good weld was indicated by one of the sheets tearing open around the weld when the sheets were peeled apart. The second method was a metallographic examination of a weld section. A homogeneous microstructure throughout the nugget indicated a good weld.

Photographic Equipment and Procedure

All photography was made with a 16 millimeter Fairchild motion analysis camera, Model HS401 with a Bl motor kit. Accessory equipment was also manufactured by Fairchild. The camera had a maximum speed of 8000 frames per sec with a 200 ft roll of film and 6400 frames per sec with a 100 ft roll of film. Maximum film capacity was 400 ft. A dc power supply (Model HS5101B) with variable voltage output drove the camera. Table 4 lists voltage settings and corresponding camera speeds.

A pair of timing lights, located in the upper part of the camera housing, placed marks on either side of the film to give an accurate time base for analyzing data. The signal for the timing lights was provided by a timing light generator (Model HS10600) which produced a square wave pulse of 450 volts peak-to-peak of 30 microseconds duration at either 100 or 1000 cycles per sec. Thus the camera speed at any position on the film could be determined by counting the number of frames between timing light marks and multiplying by 1000 (for a 1000 cps pulse).

All films were either Kodak Tri-X Reversal (TXR 430) black and white or Kodak Ektachrome ER (ERB430) color in 100 ft rolls—made especially for high speed cameras.

Two lenses were used with the camera—the first a custom made zoom lens. Successful results were obtained with this lens but the magnification was greater than required. All subsequent photography was made with a Fairchild (Model HS1004) 102.90 mm, f2.7 lens mounted on a 4 in. extension tube. This lens gave excellent results and magnified the image 1.5 times on the film. Clear welding goggle lenses were taped over the front of the camera lens to protect it from any molten steel or zinc discharged during the weld.

A microswitch connected to the squeeze time relay located in the sequence welding control started the camera.[9] Thus by varying the squeeze time, the camera drive was accelerated to the desired speed before the welding current began to flow. A squeeze time of 35 cycles would place a complete weld of 13 cycles duration at the end of a 100 ft roll of film running at approximately 6400 frames per sec.

Various combinations of lighting equipment were available. A Kliegl Brothers carbon arc light with a 2 in. parabolic microscope mirror illuminated the specimens. The arc light was powered by a Lincoln 300 amp dc arc welder. Either two or four high-intensity 750 watt spot lights were also used. These two systems were combined or used separately. The optimum lighting equipment is listed in Table 5.

It was interesting to note that although the black and white film had a much faster ASA rating (200) than the color film (125), the color film appeared to be more sensitive to the arc light than did the black and white film. This was due to the ultraviolet light produced by the arc light.

An attempt was made to use a Fairchild exposure meter to determine the optimum exposure for different camera speeds. However, since the films were calibrated for 3200K light, the exposure meter was accurate only

Table 1—Calibration of Current Control°

Tap Position	Percent Heat	Current (rms)
7	60	17,300 amp
7	62	17,500
7	65	18,300
7	68	18,900
7	70	19,400
7	71	19,650
7	72	19,900
7	73	20,200

Table 2—Calibration of Electrode Force Control*

Air Pressure, psi	Force, lb
60	430
75	600
82	650
90	740

* Note: Calibration data is valid for a throat depth of 13 in. and a horn spacing of 6.25 in.

when the spot lights were used alone. A Kodak No. 85B amber filter was tested with the color film when only the arc light was used. It improved the color but was useful only at low camera speeds due to its reduction of effective illumination. When the spot lights were used in addition to the arc light, the color was acceptable without a filter and the additional illumination allowed maximum camera speeds.

A Fairchild boresight viewfinder could be attached to the camera for focusing the lens and viewing the specimen. The viewfinder was focused on special marks on a focusing leader to accommodate for abnormalities in the operator's vision. Then the camera lens was adjusted to bring the subject into focus. This system was far from satisfactory since the focusing ring could be adjusted over a wide range with little visible change in the viewfinder but with a great change in focus when the film was viewed. Optimum focus was finally determined experimentally.

The quality of the early films was sometimes affected by the emission of white smoke from the weld. The smoke was apparently caused by either the vaporization of some zinc or some surface contaminant that was not cleaned off completely. An air line attached to the upper electrode holder directed a stream of air at the weld which blew the smoke out of the way, preventing any adverse effects on photography.

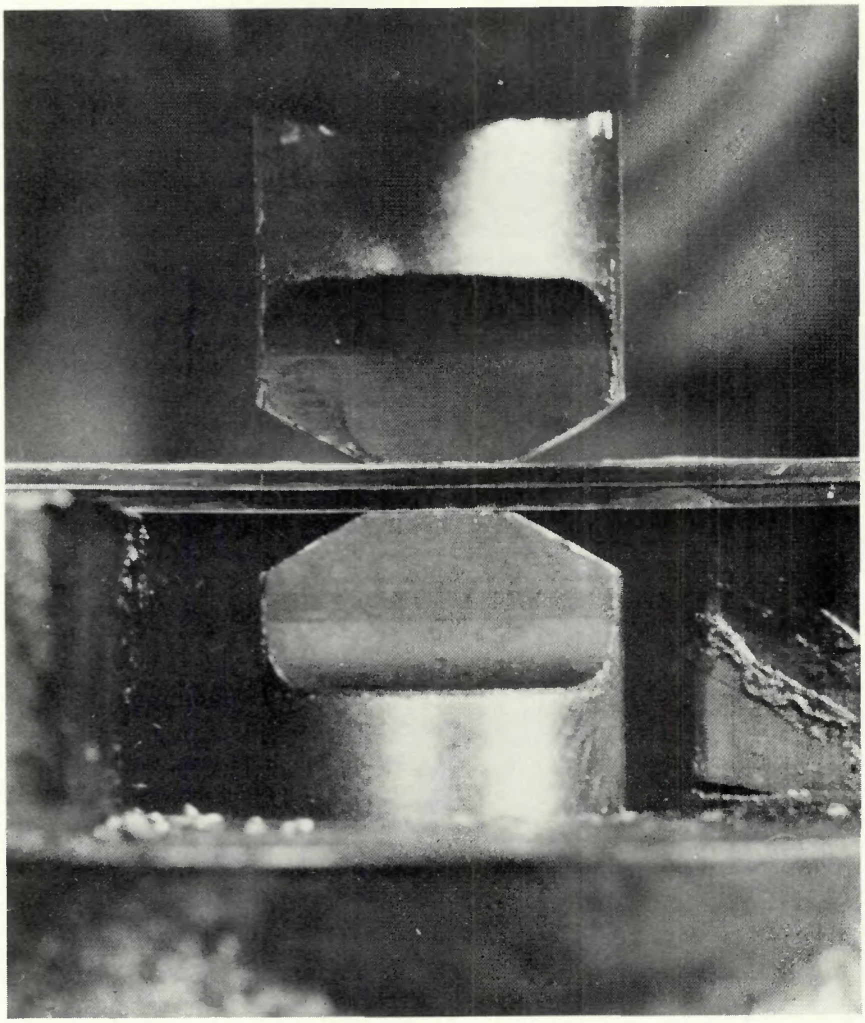

Fig. 2—Electrodes and specimens

Analysis of Films

Results of spot welding both galvanized and uncoated sheet steels are contained in 34 rolls of film listed in the Appendix. Analysis of these films consisted of viewing selected areas of each film to observe local phenomena. Areas given special attention were the electrode-workpiece and faying surface interfaces and the electrode corners. The formation of the weld nugget at the faying surfaces was also observed in detail. Some films were analyzed frame-by-frame on a small film splicer-analyzer unit to determine the exact sequence of several events that appeared to occur simultaneously.

Spot Welds in Galvanized Sheet Steel

This analysis will follow the chronological order of events seen in the photographs beginning with the first evidence of molten zinc. Black and white photographs made for this article were selected from frames of the color films. They show the progressive stages of spot welding galvanized steel in Figs. 4 through 7. However, they do not yield as much detailed information as the color films. As discussed below, the spot welding process for galvanized steel can be divided into three visually distinct phases.

The initial phase involved the melting and displacement of the zinc coating. This required the first 4 or 5 cycles of the weld current. Molten zinc was first noticed (Fig. 4a) at the faying surface when new electrodes were used. The heat loss by conduction would be much less here than at the water-cooled electrodes. The location along this interface of the first molten bubble of zinc was random within the limits of the electrodes. Since the spot welding process does not have a mechanical feature analogous to projection welding to control the location of initial melting, the location depended on several items that affect the local contact resistance. Both electrode alignment and surface cleanliness can markedly affect local contact resistance.

After a few welds had been accomplished with a pair of electrodes, the location of the first apparent molten zinc changed from the faying surface to the electrode-workpiece interface. A yellow, brass-like discoloration of the entire electrode tip was noticed after the first weld with a new pair of electrodes, indicating that they had become alloyed. This alloy on the tip of an electrode would have a higher resistance than the original unalloyed (by zinc) electrode material which would increase the local heat generation and cause the zinc coating to first melt at the electrode-workpiece interface. When the zinc coating at this interface had become fully molten, the electrode force caused it to extrude out to the electrode edges.

The greatest initial alloying effect would then occur at the electrode edges since they were in contact with a large volume of molten zinc throughout the weld. This explained the experimental observation that after several welds with a pair of electrodes, the first zinc to melt was often at an electrode edge. The location of the first molten zinc at the electrode-workpiece interface would be more typical of an industrial process which makes hundreds of welds with the same pair of electrodes.

Once the first molten region of zinc appeared, others rapidly became evident at both the electrode workpiece interface and the faying surface. These bubbles then spread together to form a fully liquid film at both interfaces as shown in Fig. 4b. The magnitude of the weld current affected the speed with which the zinc melted. A high weld current caused the zinc to be violently expelled from the interfaces, sometimes before the interfaces were completely molten. The expulsion of both the zinc and, at later stages, the steel was directed toward the camera indicating that it was promoted by the presence of the free surface.

Figure 4c shows the displacement of the molten zinc from the weld zone onto the edge of the specimen. At this point the major fraction of the molten zinc had been eliminated from the electrode-workpiece interfaces and between the faying surfaces.

The second phase of the process corresponded to the first phase of welding uncoated steel. It was the stage of the process in which the steel was heated in the center of the weld showing little visible activity in the films. This phase for galvanized steel lasted approximately 3 cycles. Heat zones, when they were not obscured by the molten zinc on the surface, could be observed as discolored regions on the edges of the workpieces.

These first two phases showed unequivocably the reasons for the increased energy required to spot weld galvanized steel. As a practical limit of current is reached, energy supplied to the weld can only be increased by increasing the weld time. Additional time was required to melt and displace zinc from the weld zone which tends to substantiate Freytag's hypothesis.[2] An increase in time for galvanized steel is also required to overcome the energy dissipated by the decreased contact resistance at the faying surface. Finally, the zinc at the electrode-workpiece interface increased the conduction heat transfer from the weld zone, requiring additional weld time to initiate a molten weld nugget.[2] Further proof was observed in a film of a weld made with 10 cycles of current (typical for uncoated steel) in which the nugget formation was incomplete.

The final phase of the welding process was the formation of a plastic weld nugget followed by melting and solidification. This required the final 5 or 6 cycles of the weld current and a brief cool down period. A pulsing phenomenon coincident with current pulses gave the first indication of nugget formation. The pulsing was characterized by an out-of-phase motion of both the electrodes and the workpieces. A yellow-red glow could be seen in the interior of the weld when the workpieces moved slightly apart as shown in Fig. 4d. The RWMA handbook described this motion of the electrodes as a "motor-action" or "jump" of current carrying members.[1] It was at this point that some molten steel was sometimes expelled from the weld. Larger weld currents and lower electrode pressures abetted this expulsion.

The yellow-red heat zones continued to grow with increasing weld time indicating that the weld nugget had become fully plastic at the edge of the workpieces facing the camera (Figs. 4e and 4f). Once this condition was reached, the increased pressure in the center of the weld due to the expansion of the molten steel was relieved and almost no steel was expelled from the weld. Symmetrical heat zones were indirectly observed on both the top and bottom electrodes as cracks or ripples in the paint on the face of the electrodes.

As soon as the nugget was plastic and fully developed, molten steel began to appear in the center and spread toward the edges as shown in Figs. 4g and 4h. Figure 4i shows a fully molten nugget. A rapid mixing of the molten steel was observed and ascribed to electromagnetic stirring. This phenomenon was previously recorded on film of projection welding by Cunningham and Begeman.[9] However, no exact stirring patterns could be detected in the thin sheet parts. Rapid heat conduction by the water-cooled electrodes maintained a solid surface which prevented nugget collapse.

Termination of the weld current was indicated by the cessation of fluid motion in the nugget. As heat continued to be dissipated into the electrodes and surrounding material, solidification began at the boundaries of the nugget and progressed to the center (Figs. 4j to 4l).

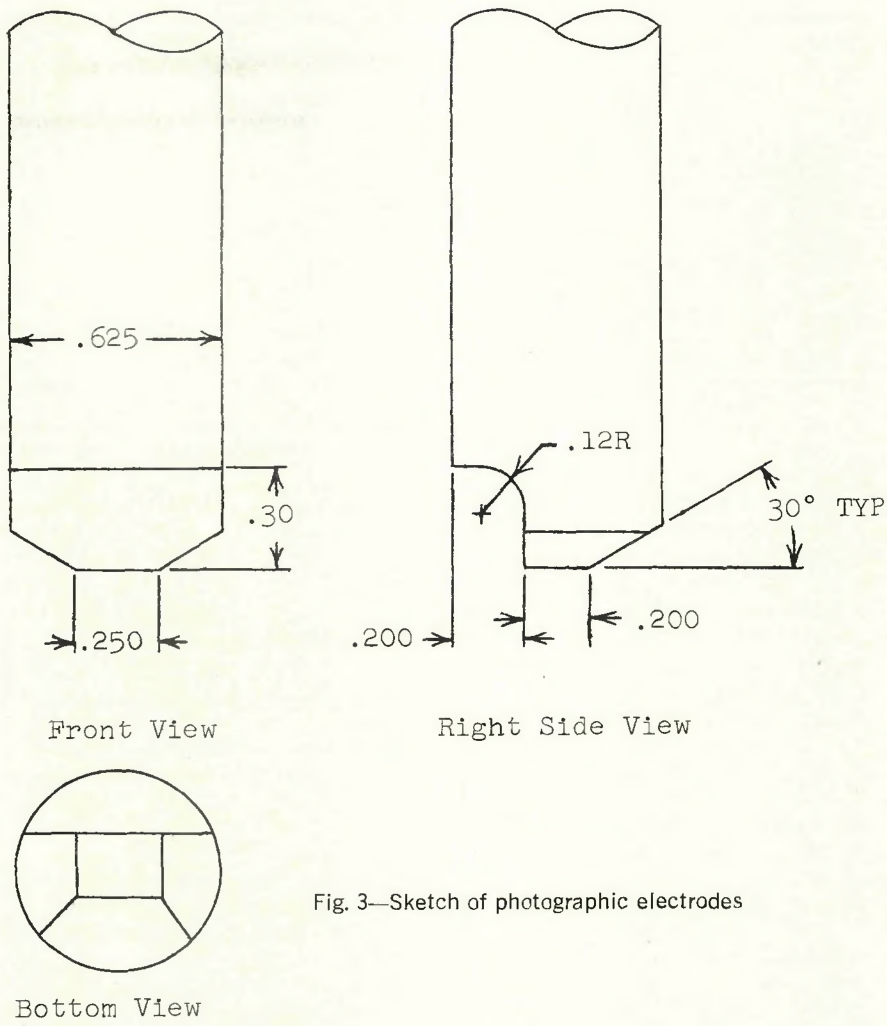

Fig. 3—Sketch of photographic electrodes

Electrode Deterioration

A set of films of electrodes in various stages of deterioration were taken. They were made at 100, 500 and

Table 3—Spot Welding Schedule

	Current for Normal Size Weld (rms), amp	Current for Nugget to Melt at edge of Specimen (rms), amp	Force lb	Weld Time cycles
Normal Spot Welding Galvanized Steel[7]	14,000	——	650	13
Spot Welding Galvanized Steel With Photographic Electrodes	18,300	19,400	650	13
Spot Welding Uncoated Steel (.048 in) with Photographic Electrodes	——	18,900	650	13
Spot Welding Uncoated Steel (.040 in With Photographic Electrodes	——	18,900	650	10–11

Table 4—Camera Power-Speed Calibration

Voltage	Nominal Operating[8] Current, amp	Speed at End of 100 ft roll, frames/sec
9	30	2100
18	—	3000
27	90	4200
40	100	4700
50	—	5600
60	135	6400

Table 5—Optimum Lighting Systems

Speed frames/sec	Light System	Lens*	Film
2100	4 spotlights	102mm	B and W
3000	Arc light	102mm	Color
4700	Arc light + 2 spotlights	102mm	Color
4700	Arc light	Zoom	B and W
5600	Arc light	102mm	B and W
6400	Arc light + 2 or 4 spotlights	102mm	B and W
6400	Arc light + 4 spotlights	102mm	Color

* Note: The aperture on the 102mm lens was always completely open (f2.7).

1000 welds. The film made at 100 welds showed a large accumulation of zinc-rich alloy on the front edge of the electrode (Fig. 5a). Large bubbles of zinc, as shown in Fig. 5b to 5f, formed at the electrode-workpiece interface and remained molten throughout the weld.

After 500 welds were made, Fig. 6a shows that the accumulation of alloy on the electrodes (this time left unpainted) was much greater, especially at the corners. The alloy built up at the corners melted a short time after the zinc coating first melted and remained molten throughout the weld (Fig. 6c to 6f).

A small cavity in the center of the upper electrode tip, shown in Fig. 6a, was noticed. The location of the cavity coincided with the location of a large zinc bubble noticed in the film taken after 100 welds (Figs. 5d and 6b). Molten zinc from the coating was extruded into the cavity and did not solidify until after the weld current had terminated.

The cavity observed in the top electrode after 500 welds had become much larger after 1000 welds (Figs. 7a and 7b) indicating that part of the alloy formed on the tip was eventually discharged. As in the previous film, the cavity was filled with molten zinc from the workpiece coating (Figs. 7c to 7f) which remained molten until well after the current was switched off. A progressively smaller nugget was observed after 100, 500 and 1000 welds.

Certain mechanisms for electrode deterioration were given support by the information obtained from these photographs. No plastic deformation of the electrodes was visible in the course of the number of welds accomplished with a single set of electrodes. Other research efforts have shown that electrode deformation is no worse when welding galvanized steel than uncoated steel.[2] The observation of a molten phase at the electrode tip throughout the weld period was consistent with Howe's proposed mechanism of a zinc-rich alloy formed on the tips of electrodes.[4]

Since the temperature at the electrode-workpiece interface has been shown to be high enough to melt a 70-30 zinc-copper alloy, the presence of a molten phase in contact with the copper electrode would indicate that the electrode could readily dissolve at the tip.[10] This material could easily be remelted on a subsequent weld and discharged, leaving a pit in the electrode. The area of the contact surface of the electrodes increased due to deposition of a zinc-rich alloy at the corners. Electrode pressure caused molten zinc with some copper in solution to extrude onto the corners. This material would continue to build up with each successive weld. Periodically, part of this alloy would be discharged, leaving a rough, pitted shoulder on the electrode tip.

Spot Welds in Uncoated Sheet Steel

A complete photographic analysis of spot welding uncoated sheet steel was not made. However, several rolls of film were made for comparison purposes, i.e., to provide contrast with the special effects encountered with galvanized steel. Of the three distinct phases of the welding process that were observed when welding galvanized steel, only the second and third phase occurred in welding plain steel since there was no coating to contend with. The same "motor action" pulsing was observed for the plain steel as the galvanized steel but at an earlier period in the weld time. Reflected light caused by a gap between the workpieces when the electrodes pulsed appeared as a narrow white line at the faying surface. This was the first indication that the welding current had begun.

On subsequent current pulses the line reappeared, gradually growing into a yellow-red heat zone. After several cycles of current, one or sometimes two heat zones of darker color would appear and rapidly spread across the surface. Heat zones in plain steel were thicker than the ones noticed in galvanized steel. This was due to the higher contact resistance at the electrodes which increased heating in that area and decreased heat conduction from the faying surface, thus allowing quicker nugget formation. A white oxide film formed on the surface with the same geometry as the preceding heat zones.

The nugget formed as a plastic zone with the same shape as the heat zone and oxide film. Formation of the nugget, followed by melting and solidification, was quite similar to nugget formation and solidification in galvanized steel. The same eddy currents noticed in the galvanized steel were also observed. As predicted by existing welding schedules, less current and time were required for welding the uncoated steel.

No electrode deterioration was observed for the uncoated steel, which

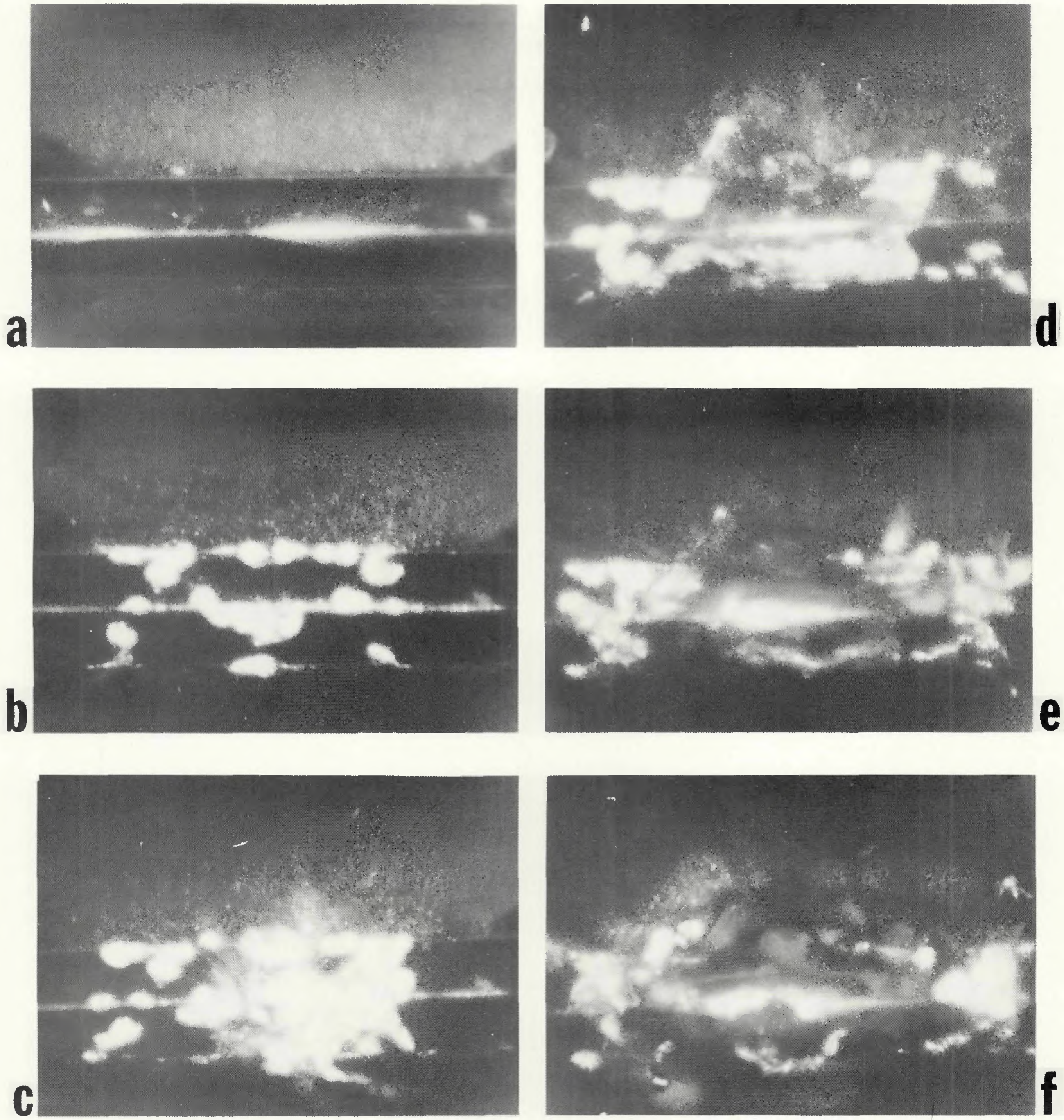

Fig. 4—Sequence of welding process for new electrodes: (a) Zinc coating begins to melt, (b) completely molten coating, (c) coating displaced from weld zone, (d) weld nugget begins to form, (e) small plastic nugget, (f) completely plastic nugget

would have only been evident after several hundred welds.[11]

Conclusions

This photographic technique provides a detailed observation of the sequence of events that occur in the spot welding of galvanized steel. Weld time can be divided into three phases: Molten zinc is first observed at either the faying surface for new electrodes or at the electrode-workpiece interface for used electrodes due to an increase in contact resistance of the alloyed tip. Zinc is subsequently displaced from the weld zone by electrode pressure. This phase requires the first 4 or 5 cycles of the weld current.

The second phase occupies approximately 3 cycles of weld current. Little visible activity occurs during this stage other than the formation of heat zones which are generally obscurred by the zinc that has extruded onto the edge. This period is obviously necessary for formation of the nugget in the interior of the weld which would ultimately grow to the edge of the sheet. These two phases show why additional weld time is necessary for galvanized steel.

The remaining weld time is needed for growth of the nugget. A pulsing heat zone gives the first indication of nugget formation. The yellow-red

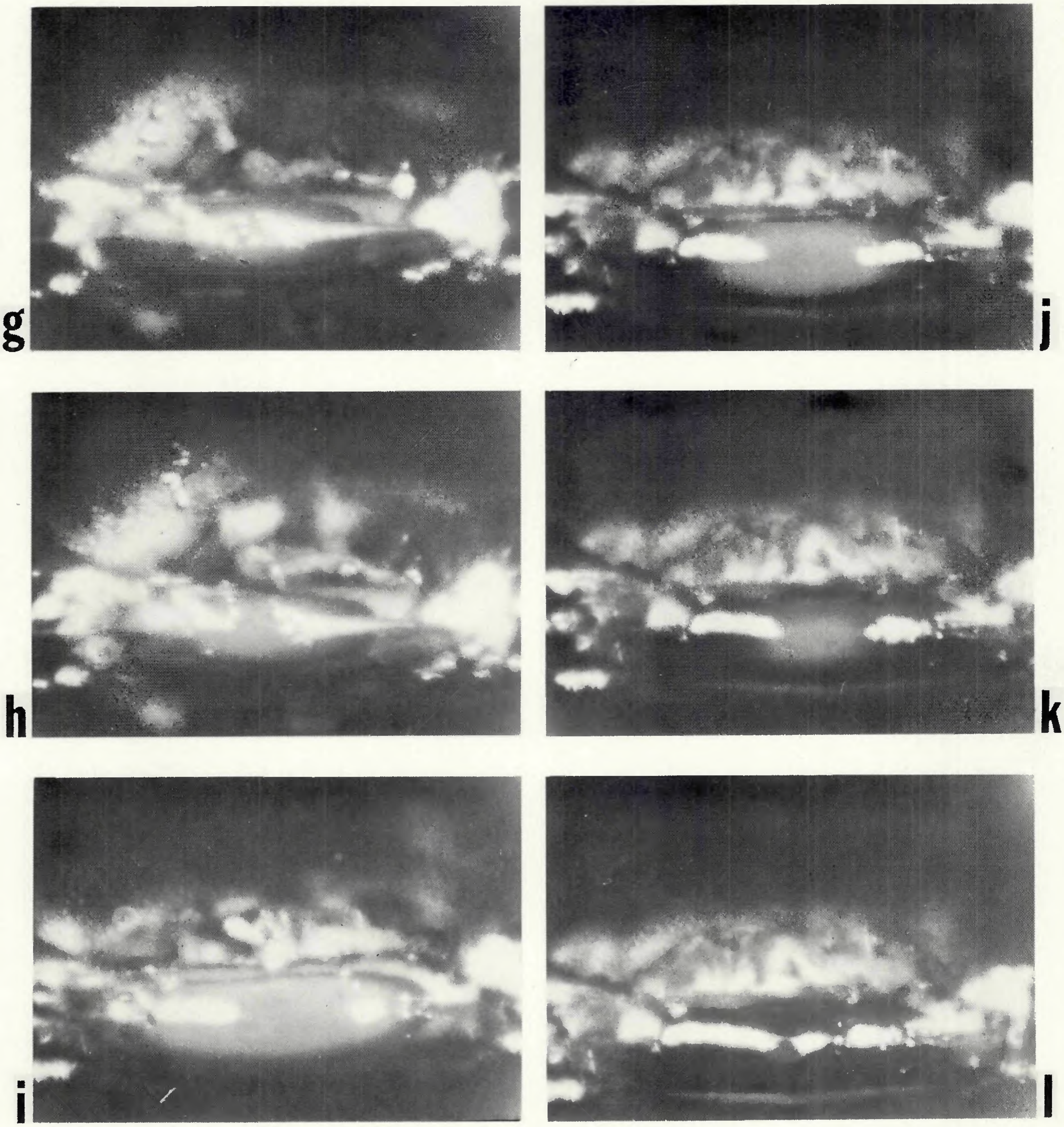

Fig. 4 (continued)—(g) plastic nugget begins to melt, (h) nugget partially molten, (i) completely molten nugget, (j) solidification begins, (k) solidification nearly complete, (l) solidification complete.

zone gradually grows to an elliptical shape and then melts. An electromagnetic stirring of the molten steel is observed but no symmetrical flow patterns are established. After the weld current ceases, heat rapidly dissipates into the water-cooled electrodes. Solidification thus begins at the boundary of the nugget and progresses to the center.

Two mechanisms of electrode deterioration when welding galvanized steel are given support by this investigation. Inspection of an electrode after a weld reveals a small amount of zinc that has solidified on the edge. After many welds, a large quantity of zinc-rich alloy has deposited on electrode corners. In general, however, the most plausible explanation of electrode deterioration seems to be the one that proposes a compositional change of an electrode tip caused by continuous contact with molten zinc.

Photographic analysis not only gives visual proof that the electrode remains in contact with molten zinc throughout the weld but also proves that the alloy formed on the electrode tip melts during a weld and may be discharged, leaving a small pit in the tip. This process repeats on subsequent welds causing large pits or cavities in the electrodes as well as shortened electrode life.

High speed photography is an ex-

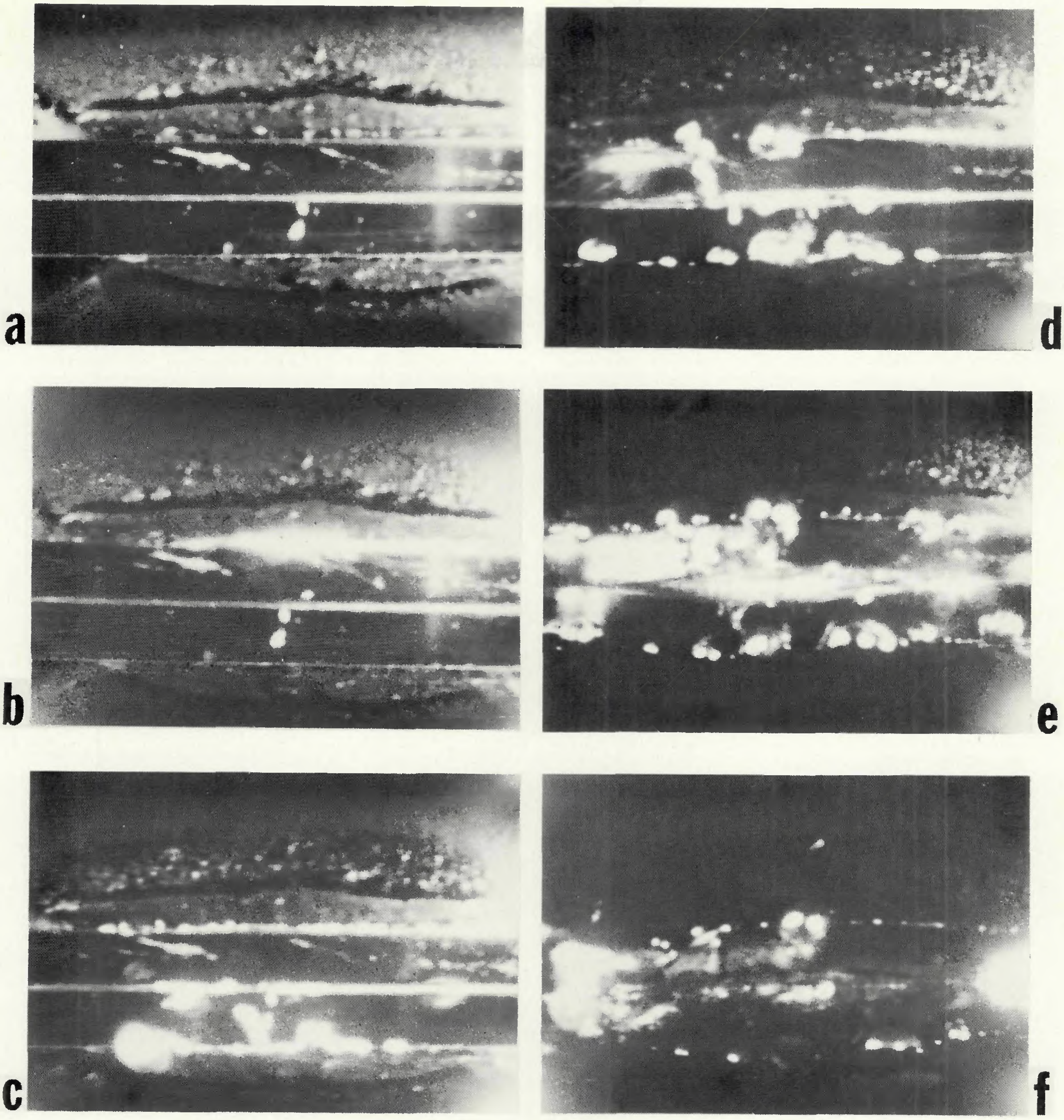

Fig. 5—Sequence of photographs of welding process for 100 welds made with electrodes: (a) Condition of electrodes, (b) zinc coating begins to melt, (c) zinc molten at interfaces, (d) nugget begins to form, (e) nugget completely formed, (f) molten zinc at interfaces after current terminates

tremely useful research tool for analysis of processes that occur over a short period of time. It can show the step-by-step progress of a spot weld in galvanized steel from the first sign of molten zinc to the end of solidification. Visual information helps define a mechanism of electrode deterioration and shows why weld time has to be increased for welding galvanized steel. A visual summation of these results is available in a composite film.

There are several areas of study that should help solve the problem of electrode deterioration. A solution to the heat checking of a molybdenum cap would be very helpful.[2] High speed photography as described in this study lends itself to analyzing one of these caps in use. An analysis of heat zone and nugget formation in uncoated steel would be useful for comparison with any future experiments with different electrode compositions or geometries.

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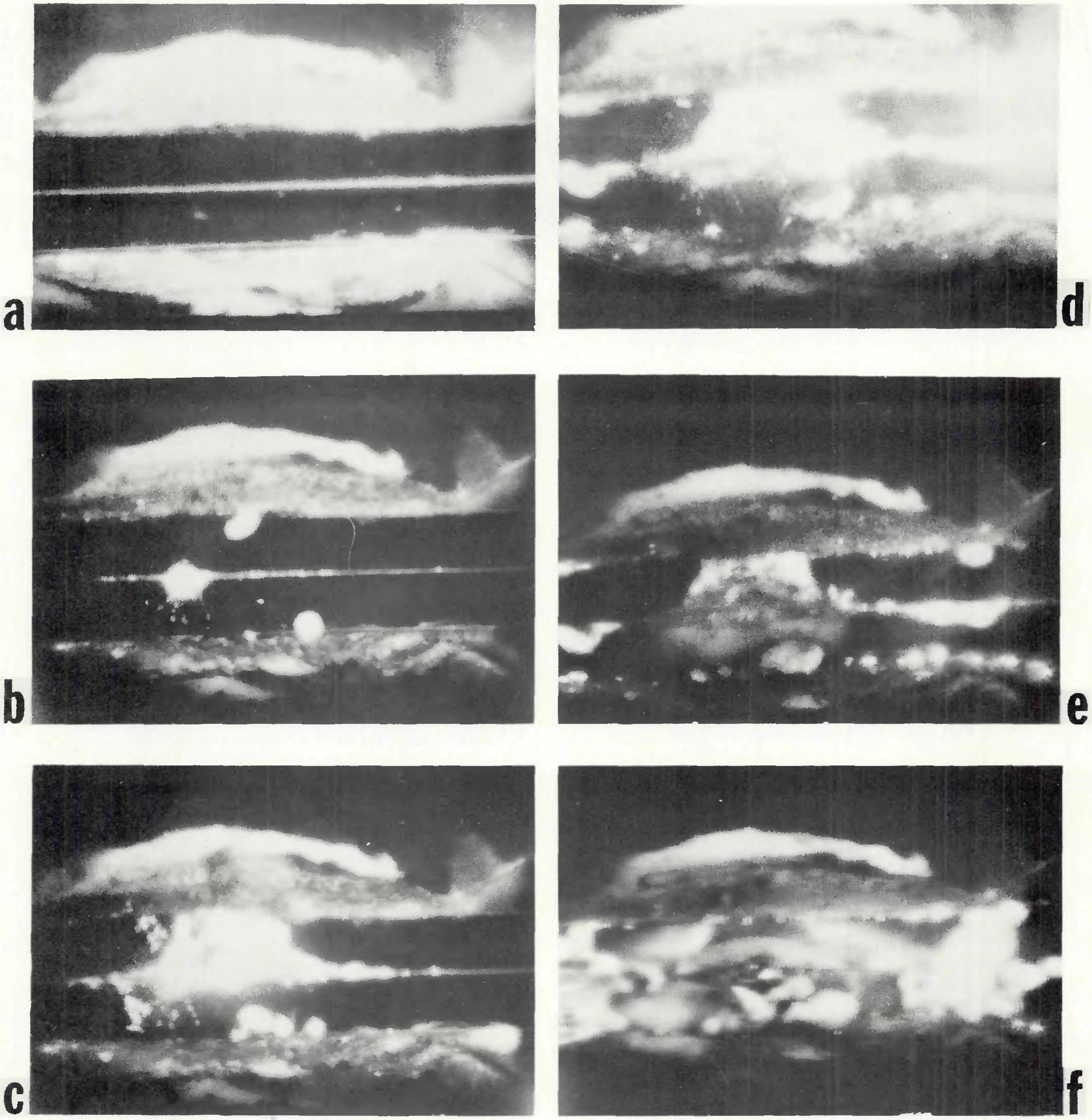

Fig. 6—Sequence of photographs of welding process for 500 welds made with electrodes: (a) Condition of electrodes, (b) zinc coating begins to melt, (c) zinc molten at interfaces, (d) nugget begins to form, (e) nugget completely formed, (f) molten zinc at interfaces after current terminates

ard Webb's technical assistance, especially with the high speed photographic equipment, is gratefully acknowledged.

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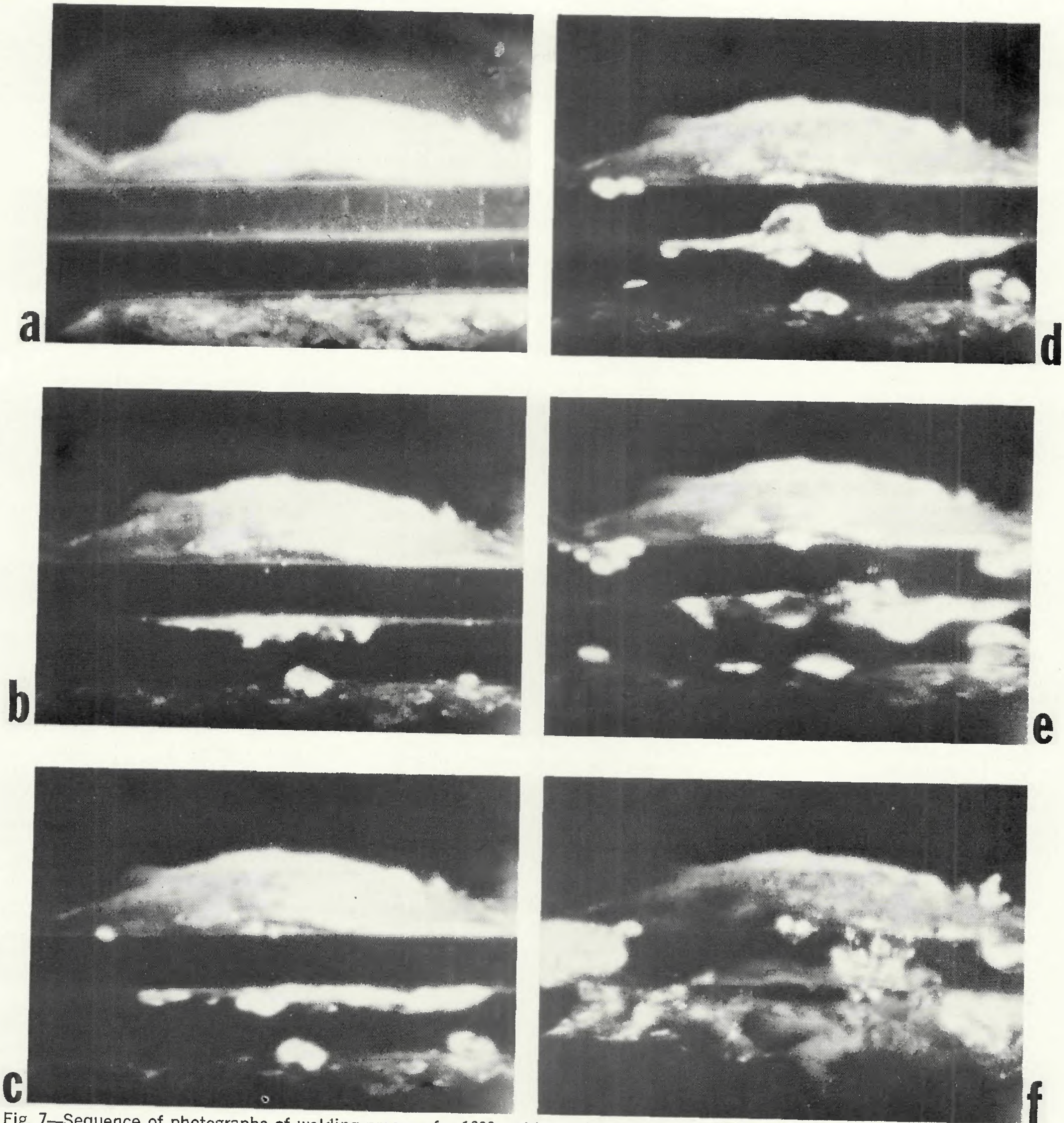

Fig. 7—Sequence of photographs of welding process for 1000 welds made with electrodes: (a) Condition of electrodes, (b) zinc coating begins to melt, (c) zinc molten at interfaces, (d) molten zinc in cavity, (e) nugget completely formed, (f) molten zinc in cavity after current terminates

Appendix of Films

For those of you who are actively involved in photography, the author presents below details of his technique as well as experimental results.

Roll 1. Galvanized steel: current, 18-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 10 cycles; Tri-X film camera speed, 2100 fr/sec; focus, 3.5 ft; f2.7; lighting system, 4 spotlights. Results: weld was bad.

Roll 2. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 60 cycles; Tri-X film; camera speed, 2100 fr/sec; focus, 3.5 ft; f2.7; lighting system, 4 spotlights. Results, camera did not start until weld current started. Camera hooked up to current relay instead of squeeze time relay.

Roll 3. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 60 cycles; Tri-X film; camera speed, 2100 fr/sec; focus, 5 ft; f2.7; lighting system, 4 spotlights. Results, slightly overexposed, fairly good film.

Roll 4. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 60 cycles; Tri-X film; camera speed, 4200 fr/sec; used zoom lens; lighting system, arc light. Results, very underexposed.

Roll 5. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 60 cycles; Tri-X film; camera speed, 6400 fr/sec; used zoom lens; lighting system, arc light. Results: very underexposed.

Roll 6. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 60 cycles;

Tri-X film; camera speed, 4700 fr/sec; used zoom lens; lighting system, arc light (refocused). Results: very overexposed.

Roll 7. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 15 cycles; Tri-X film; camera speed, 6400 fr/sec; used zoom lens; lighting system, arc light. Results: very overexposed and bad focus.

Roll 8. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 15 cycles; Tri-X film; camera speed, 4700 fr/sec.; used zoom lens; lighting system, arc light. Results: good, slightly underexposed, shows zinc melt and pulsing phenomenon.

Roll 9. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 6.5 ft; f2.7; lighting system, arc light. Results: good photography, shows zinc progressively melting, shows pulses and some heat zones, but nugget does not melt all the way to viewing surface, weld emits some white smoke.

Roll 10. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 6.5 ft; f8; lighting system, arc light. Results: underexposed.

Roll 11. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Ektachrome film; camera speed, 3400 fr/sec; focus, 6.5 ft; f2.7; lighting system, arc light. Results: focus bad, need filter, speed too slow.

Roll 12. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 40 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 50 ft; film plane-to-specimen distance—21 in.; mirror-to-specimen distance, 3 in.; f2.7; lighting system, arc light. Results: focus bad.

Roll 13. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 40 cycles; Ektachrome film; camera speed, 4700 fr/sec; focus, 20 ft; f2.7; used amber filter (Kodak Type B No. 85B); lighting system, arc light. Results: focus bad.

Roll 14. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; used fan to blow away smoke; Tri-X film; camera speed, 6400 fr/sec; focus, 11.5 ft; f2.7; lighting system, arc light. Results: focus bad.

Roll 15. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed 5400 fr/sec; focus, 3.2 ft; film plane-to-specimen distance, 15.06 in.; f2.7; lighting system, arc light. Results: focus fairly good, no weld.

Roll 16. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 5400 fr/sec; focus, 3.75 ft; f2.7; lighting system, arc light. Results: focus good, shows molten zinc and small plastic nugget.

Roll 17. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 5400 fr/sec; focus, 5 ft; f2.7; lighting system, arc light. Results: focus very good, some liquid between workpieces prevented weld.

Roll 18. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 5400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, melting of zinc begins at electrode interface.

Roll 19. Galvanized steel; current, 18,-300 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Ektachrome film; camera speed, 4700 fr/sec; focus, 4.5 ft; f2.7; used amber filter; lighting system, arc light plus 2 spotlights. Results: good color analog of Roll 9.

Roll 20. Galvanized steel; current, 19,-400 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, nugget melts on viewing surface of workpieces, violent liquid steel agitation, electrodes virtually ruined by previous trial weld with excessive current.

Roll 21. Galvanized steel; current, 19,-900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, observed 3 distinct phases of activity during weld, nugget did not completely melt, smoke still a problem.

Roll 22. Galvanized steel; current, 19,-900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 30 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, completely molten nugget, smoke still a problem.

Roll 23. Galvanized steel; current, 19,-900 amp; electrode force, 430 lb; weld time, 15 cycles; squeeze time, 33 cycles; used air line to blow smoke away; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, shows heat zones, low electrode force did not contain weld very well, should use new electrodes for next film to eliminate alloying effect of zinc and permit lower current.

Roll 24. Galvanized steel; current, 19,-400 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography (slightly underexposed), zinc began to melt at faying surface with new electrodes, shows formation of fully molten nugget with minimum of expulsion.

Roll 25. Galvanized steel; current, 19,-600 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good except a loose film chip obscures part of picture.

Roll 26. Uncoated steel (0.048 in. thick); current, 18,300 amp; electrode force, 650 lb; weld time, 11 cycles; squeeze time, 37 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, nugget did not fully develop on surface.

Roll 27. Uncoated steel (.048 in. thick); current, 18,900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography (somewhat underexposed), fully molten nugget.

Roll 28. Uncoated Steel (.048 in. thick); current, 18,900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Tri-X film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 2 spotlights. Results: good photography, shows nugget formation and heat zones.

Roll 29. Galvanized steel; current, 19,-400 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 4 spotlights. Results: good photography (exposure much better), nugget does not fully form, shows heat zone on electrodes.

Roll 30. Galvanized steel; current, 19,-900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 4 spotlights. Results: good photography, nugget did not form (apparently electrodes are not making good electrical contact with electrode holders).

Roll 31. Galvanized steel; current, 19,-600 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 4.5 ft; f2.7; lighting system, arc light plus 4 spotlights. Results: focus bad (apparently camera had moved slightly).

Roll 32. Galvanized steel; current, 19,-600 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 5.5 ft; f2.7; lighting system, arc light plus 4 spotlights. Results: focus bad.

Roll 33. Galvanized steel; current, 19,-600 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ekachrome film; camera speed, 6400 fr/sec; focus, 3.5 ft; film plane-to-specimen distance, 14.75 in.; f2.7; lighting system, arc light plus 4 spotlights. Results: focus bad.

Roll 34. Galvanized steel; current, 19,-900 amp; electrode force, 650 lb; weld time, 13 cycles; squeeze time, 35 cycles; Ektachrome film; camera speed, 6400 fr/sec; focus, 3.5 ft; film plane-to-specimen distance, 15.02 in; f2.7; lighting system, arc light plus 4 spotlights. Results: good photography, shows nugget develop very well but current somewhat too high.