Measurement of Dynamic Electrical and Mechanical Properties of Resistance Spot Welds

Displacement curves and dynamic resistance provide significant data for evaluating nugget quality

BY S. A. GEDEON, C. D. SORENSEN, K. T. ULRICH AND T. W. EAGAR

ABSTRACT. Although many different sensors have been used to evaluate the quality of resistance spot welds, no single sensor has found universal application. Some of the most popular of these sensors are weld voltage, current, dynamic resistance, and electrode displacement; however, many problems are encountered in obtaining signals that are uncorrupted by the high electrical interference of the process itself. In the present paper, methods of reducing errors in the measurement of dynamic voltage, current, force, and displacement are presented as a guide to new or less experienced users of such sensors, who may not recognize some of the practical problems that may be encountered. Finally, an example of how these signals may provide information about the spot welding process is discussed.

Introduction

Resistance spot welding (RSW) is one of the cleanest and most efficient welding processes for steel sheet; however, one of its greatest weaknesses is the difficulty of performing reliable nondestructive tests of the joint. No reliable, economical method of inspecting the completed weld has been developed. Instead, many people have attempted to develop a monitor of the process that can provide some assurance that the weld schedule is under control. Unfortunately, simply having a good weld schedule may be inadequate when workpiece variations, electrode tip wear, and machine variations are considered. It would be desirable to relate some of the monitoring sensor outputs to the nugget growth. This would permit a feedback controller to be designed, which would hopefully improve the reliability of the process.

To reduce the risk of part failure, manufacturers often require that more welds be performed than would be needed if each weld were more reliably produced. In order to provide process uniformity, electrode tips may be dressed frequently, with a resulting loss of productivity. Quality assurance schemes used in the past have ranged from shutting off the current after expulsion occurs to the use of a large number of destructive tests (Ref. 1). However, destructive tests can only be made on a sample basis and may miss a large number of defective welds.

Many attempts have been made to perform nondestructive inspection and characterization of the size and quality of a spot weld. One of the earliest and simplest techniques is monitoring the voltage between the electrode tips. If the welding current is approximately constant, the voltage will be proportional to the heat generated between the electrode tips. Unfortunately, the welding current is generally not constant due to the changing resistance of the weld area. In addition, recent studies in our laboratory show that, when welding galvanized steel, most of the resistance variations during the course of the weld occur at the electrode-sheet interfaces and not at the faying interface. Hence, at least in galvanized steel, voltage variations from weld to weld may be related more to electrode wear than to heat generation at the faying interface, where the nugget is expected to form. Nevertheless, a number of adaptive control units have been developed which sense the voltage and shut off the current at some predetermined voltage level (Refs. 2–5). Such units often work well on bare steel, but are not effective on galvanized steel.

Other controllers sense only the welding current and signal a fault when the measured value does not fall within prescribed limits. If the weld voltage is constant, then the weld current is proportional to the heat generated in the weld. However, as previously mentioned, if the resistance of the weld changes, the weld voltage will change also. Thus, in order to adequately measure power input to the weld, both voltage and current must be measured. This is done in many commercial systems; however, the total power across the electrodes does not differentiate between heating near the electrodes and heating at the faying interface. As noted above, in galvanized steel, this can lead to significant errors.

In addition to the problem of changing weld resistance, a number of other problems arise when trying to measure voltage or current alone. During the first few half cycles of the weld, the resistance changes rapidly. Thus, an average current or voltage reading can be greatly influenced by these cycles, particularly in short-time welds. There are also turn-on transients in many RSW machines which can affect the data collected near the start of the welding sequence. For these

KEY WORDS

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S. A. GEDEON, C. D. SORENSEN, K. T. ULRICH and T. W. EAGAR are with the Materials Processing Center, Massachusetts Institute of Technology, Cambridge, Mass.

reasons, it is often advisable to ignore the first cycle or two of data. Yet another common problem is the power factor on the overall electrical load of the manufacturing plant. Large changes in power serving other equipment can significantly alter the power output of the RSW machine. This can be of particular concern in plants with multiple RSW machines. Fortunately, RSW equipment suppliers have provided several types of control circuits for reducing this problem for many years and this circuitry is continually improving. Another difficulty, when monitoring either the welding current or voltage, is the noise associated with the large currents required for welding. This problem will be addressed in the section on noise reduction.

A more elaborate method of measuring RSW quality is temperature monitoring by infrared emission (Ref. 6). These techniques have not been satisfactory to date because of variable emissivity and the expense of self-correcting systems (Ref. 7).

Acoustic emission can be used to indicate when expulsion occurs (Refs. 8, 9), but it is not presently useful for monitoring weld nugget growth (Ref. 10). Ultrasonic inspection (acoustic transmission) has been studied (Refs. 11–13), but real-time adaptive feedback control has been unsuccessful. Furthermore, the minimum detectable flaw size is often too large to be acceptable in small resistance spot welds. Reflective noise from the large surface area of the thin sheets usually used in RSW may be prohibitive to the development of a real-time ultrasonic monitor.

More satisfactory results have been obtained through monitoring of the electrode displacement during a weld schedule. The amount of thermal expansion, melting and expulsion can be correlated to the slope and magnitude of the displacement curve. Quality control through the use of this easily obtainable information has been used for some time (Refs. 14–19), although many users consider it applicable only to press welders and not to portable welding guns. The electrode force has also been monitored and adjusted, but only to ensure that it is within certain predetermined limits (Ref. 19). In our own work, we do not find large variations in force during a single weld; hence, measurement of the dynamic force provides little useful information.

Finally, the dynamic resistance can be obtained by dividing the voltage by the current. There are often significant differences in the methods used to calculate this dynamic resistance. Nonetheless, a number of interesting phenomena can then be observed by relating the resistance variations to fritting, breakdown of surface asperities, heating, melting, and expulsion of the various materials between the electrodes. This technique is currently receiving much attention (Refs. 19–25), though it also has problems (Ref. 26). Most investigations measure the dynamic impedance rather than resistance; however, at small phase shifts, the two are nearly equivalent and are probably equally effective as a means of quality control.

Generally, it is found that most investigations which monitor only one parameter, even if it is monitored dynamically (*i.e.,* as it changes during the course of the weld), have not been entirely successful. Investigations which have used a number of sensors, however, have met with more success, as different sensors have better sensitivity to different problems which may arise. Since no single sensor has been found that can monitor all of the potential problems affecting resistance spot weld quality, it is believed that improved spot weld controllers will require multiple sensors. The more sensors, the better, although there is obviously a cost-benefit tradeoff to be considered as well. In the present work, it was believed that measurement of voltage, current, force and displacement might provide the complementary information necessary to more accurately describe the process. These were chosen by considering the fact that RSW is an electro-mechanical process, and these four parameters should adequately describe both the electrical and mechanical changes that occur during the process.

Although a number of previous researchers have monitored one or more of these parameters, it was found that the reports were not always precise about methods used for sensing and processing the information. Thus, it is felt that a discussion describing the various sources of measurement error, along with methods of eliminating or reducing this error, will be useful.

Fundamentals of Instrumentation Noise Reduction

Accurate measurement of the information of interest is necessary in any control system or quality monitor. The development of an accurate system of resistance spot welding instrumentation must precede any work in welding control.

A spot welding machine is a hostile environment for instrumentation. The very large currents needed for welding produce electrical noise which can easily mask the electrical signals being monitored. Fortunately, if the principles behind the generation of electrical noise are properly understood and utilized, signal corruption can be minimized.

There are two major classes of electrical noise: radiative and inductive. These two classes of noise can be distinguished by the fact that radiative noise has the same shape as the noise source voltage, while inductive noise is proportional to the derivative of the noise source voltage. Radiative pickup of noise is exhibited when a traveling electromagnetic wave impresses its time-varying voltage upon a conductor. Induced pickup of noise occurs when a loop of wire is placed in a time-varying magnetic field. The induced voltage generated in the loop will be proportional to the area of the loop, the strength of the magnetic field, and the angle the loop makes with the field. This relation is given by Faraday's law

$$V = dI/dt\ A \cos\theta \qquad (1)$$

where V is the voltage, dI/dt is the change in current with respect to time, A is the area of the loop, and θ is the angle of the loop to the magnetic field.

Because the origins of radiative and inductive noise are different, the methods of reducing them are different. The most common way to reduce radiative noise is to enclose the signal-carrying wire in a grounded conductor. This grounded conductor absorbs the electromagnetic waves, preventing them from creating a noise voltage on the signal-carrying wire. This is the principle of shielding used in coaxial cables. It should be noted that coaxial cable provides no protection from the pickup of induced voltages as low-frequency magnetic fields easily penetrate the ground sheath.

At high voltages, the primary noise is caused by radiation, while at the high currents used in resistance spot welding, the primary noise is caused by induction. Unfortunately, eliminating inductive noise is more difficult than eliminating radiative noise. Since the welding currents used in RSW are so large, elimination of inductive noise is essential.

One technique that is very effective in minimizing induced voltages is the twisted pair. By twisting the two signal-carrying wires tightly together, the area of the loop is minimized and the orientation is constantly altered such that the induced voltage is essentially reduced to zero. It has been found that shielded twisted pairs provide the optimum protection from both radiative and inductive pickup of unwanted signals or noise at the frequencies of spot welding. In visiting many welding laboratories and shops, the authors often find coaxial instrumentation cables in use when twisted pairs are more appropriate. Indeed, some suppliers of commercial RSW equipment fail to utilize these simple principles of noise reduction.

All instrumentation described in the following section used shielded twisted leads whenever possible. In addition, other methods were used to eliminate or reduce noise and experimental error.

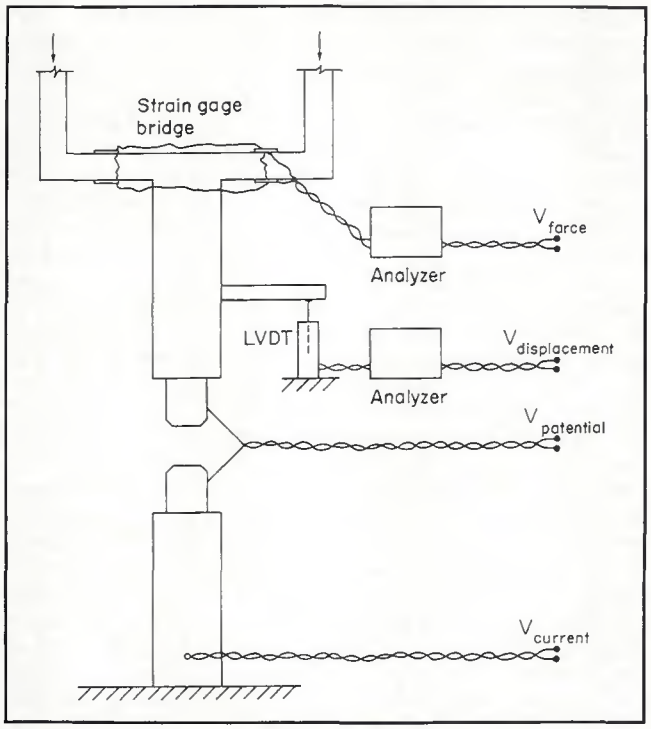

Fig. 1 — Instrumentation configuration, showing the four monitoring signals used for this study

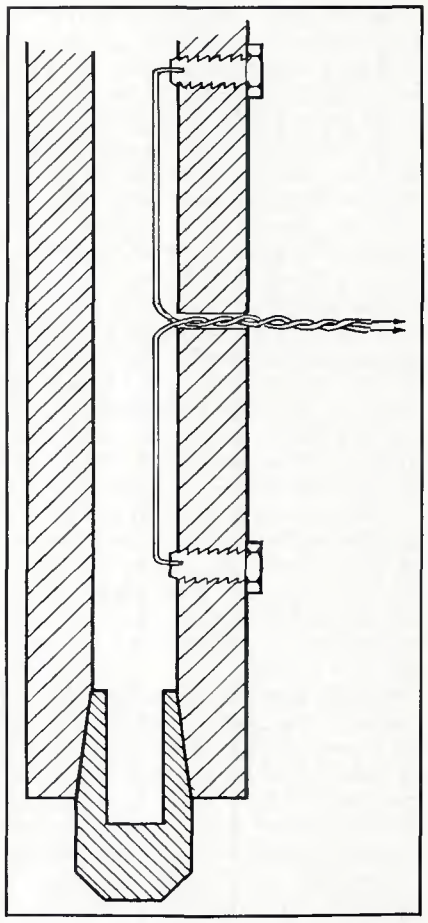

Fig. 2 — Cross-section of electrode holder, showing modifications made to allow the holder to function as a shunt. Holes were drilled in the ends of two ¼-28 bolts, wires were soldered in the holes, and the bolts were inserted into drilled and tapped holes in the electrode holder. Silicone rubber sealant was used to plug the wire exit hole and prevent cooling water from leaking

Methods of Obtaining Accurate Physical Data

Several methods of measuring the weld current, voltage, displacement and force were analyzed in this study. Some of the instrumentation that was used was purchased from commercial sources, whereas other sensors were specially designed and fabricated in our laboratory. A schematic of the instrumentation configuration is shown in Fig. 1.

Current Measurement

There are two methods of measuring spot welding current commonly found in the literature: toroidal coils and Hall-effect probes. The toroidal coil, which is used in the majority of spot welding research projects, measures voltages induced by the changing magnetic fields surrounding the weld current carrying conductors. The toroid presents a known loop area which picks up an induced voltage from a time-varying magnetic field. As such, it is only useful for measuring AC currents. This voltage signal can be electronically integrated to provide an indirect measurement of the welding current, as can be seen from Faraday's law (Equation 1). Variations in the position and orientation of the toroid, however, can cause variations in the effective area and hence in the measured value of the current. Our studies have shown that this error can be as large as 5% of the reading when simply hanging the toroid on the horn of the RSW machine, although we have reduced it to less than 2% by providing a wooden mount that always holds the toroids in the same position on the horn. The Hall-effect probe, which is more accurate and more expensive, measures the voltage across a semiconductor due to surrounding magnetic fields and is thus also an indirect measurement of the current. The voltage produced by the Hall probe is of the form of Equation 1, although the constant A is different. Therefore, this probe is also sensitive to variations in orientation and position.

The system used to measure current in this study was a resistive shunt. Although this is a standard way of measuring low amperages or DC currents, it is usually unsuitable for RSW applications. This is because the leads which measure the voltage across the shunt must be several inches apart, and the resulting loop is large enough for the induced voltage to easily corrupt the desired signal, which is often only a few millivolts. This problem was overcome by using the cylindrical electrode holder as the shunt, as is shown in Fig. 2. The voltage leads were connected on the inside of the conductive holder where the magnetic field is zero due to symmetry. The leads exit the holder as a twisted pair, thus minimizing the effect of induced voltages. The shunt was calibrated with a DC power source, by passing a series of known currents through the electrode holder and measuring the respective voltages. This shunt had a resistance of 3 $\mu\Omega$ and gave a signal of 60 mV corresponding to a current of 20 kA. This method of current measurement gives a clean, largely uncorrupted signal directly related to the actual welding current. It avoids the integration errors of the toroid and is much less expensive than the Hall probe.

An example of the current waveform generated with our system is shown in Fig. 3. Our study concentrated on hot-dipped and galvannealed steel; the figure shown is typical of a hot-dipped material.

Voltage Measurement

The spot welding voltage signal obtained on the secondary of the transformer is quite small and thus can be very easily corrupted. The voltage drop must be measured across a workpiece which has some finite thickness. Since the voltage probes must span the thickness of the workpiece, a loop will exist in the voltage-sensing circuit through which magnetic flux will generate noise. This problem becomes much worse when the voltage leads must follow the arms and encompass the entire throat of the welding machine, as is true in most production

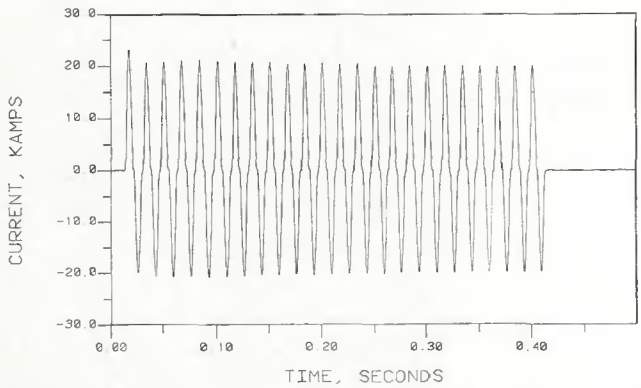

Fig. 3 — Dynamic weld current curve using current shunt (75% I, 24 cycles)

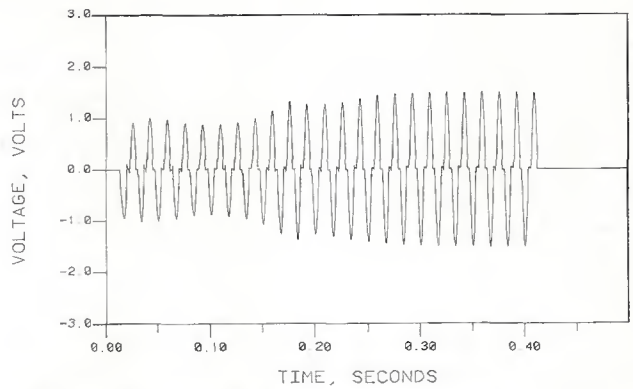

Fig. 4 — Dynamic weld voltage curve (75% I, 24 cycles)

applications. Watney and Nagel (Ref. 26) have described one means of correcting this induced voltage noise by manipulation of the data in the computer. In the laboratory, it is easier to minimize the area of this loop, thus reducing the induced noise voltages to a low level. In order to further reduce the induced noise, a compensating loop was added to our voltage sensor. The size and orientation of this secondary loop was adjusted such that the induced voltage of this loop cancelled the induced voltage of the voltage sensor loop. While such a solution is not practical in a production environment, for laboratory studies, the induced voltage in the monitored signal can be reduced to an acceptable level. A typical example of a dynamic voltage signal monitored with this system is shown in Fig. 4.

Commercially, it is more practical to monitor the primary voltage. This provides a larger signal and hence a better signal-to-noise ratio. However, when monitoring the primary voltage, the voltage drop in the transformer and entire secondary circuit is measured. Thus, the weld voltage is a smaller portion of the measured voltage. This may not create problems when attempting to make relative measurements of voltage, but it cannot provide absolute values of the voltage drop in the part, which may be of interest in the laboratory.

Force Measurement

Weld force was measured with a full-bridge strain gauge mounted on a polycarbonate beam that replaced the steel crosshead of the welding machine. The forces on the crosshead cause a bending moment and deflection in the beam. The polycarbonate beam was used because its lower elastic modulus introduced larger deflections, which increased the signal level of the strain gauge, thus giving a higher signal-to-noise ratio. The strain gauge was interfaced with a BLH Electronics Model 1200 strain analyzer and calibrated with a proving ring. It is very important that the leads from the individual strain gauges are twisted, because the output from the strain gauges are on the order of 10 mV, which could be easily corrupted. An example of the force curves for a good weld and a weld exhibiting expulsion are shown in Figs. 5 and 6.

The dynamic forces obtained by this method are different from the forces actually experienced at the electrode tips, although in static equilibrium, they should be equal. In dynamic loading, they will differ by the product of the mass and acceleration of the welding head. The actual force on the weld could be calculated by attaching an accelerometer to the welding head. Perhaps a better method of measuring force would be to use a lower inertia head or a piezoelectric load cell (Ref. 19) in the welding head close to the electrodes. It has not yet been determined how precisely the force needs to be monitored.

Displacement Measurement

A Monitell commercial spot welding monitor system (System Monitors and Controls) was used to measure electrode displacement. This device uses a linear variable differential transformer (LVDT) to produce a voltage proportional to displacement. This type of monitoring device is quite common and has been used extensively for extracting information from the RSW process. The output from the Monitell unit was approximately 15 mV per 0.001 in. displacement. Shielded twisted leads were used to minimize corruption of the signal. A typical displacement curve of a good weld on hot-dip galvanized steel sheet is shown in Fig. 7. The shape of this curve will be explained subsequently.

Data Collection

As an illustration of the way in which these sensors may be used to study the spot welding process, several examples from studies of hot-dip galvanized, galvannealed and bare steel will be presented. All welds were made with a 75-kVA Taylor-Winfield pneumatic press welder equipped with Technitron controls for the ignitron tubes.

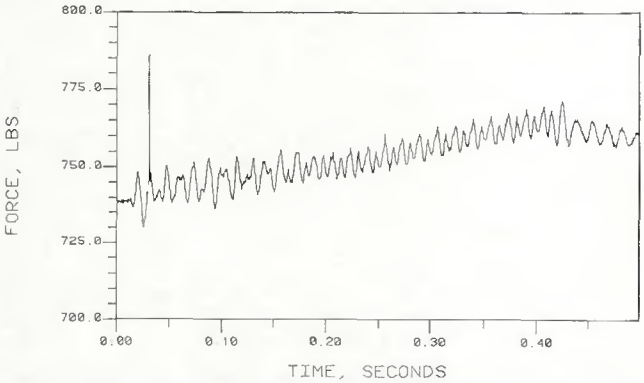

Fig. 5 — Dynamic force curve for a weld without expulsion

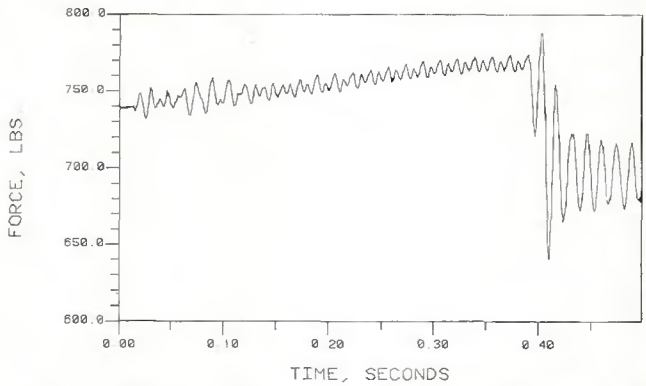

Fig. 6 — Dynamic force curve for a weld with expulsion

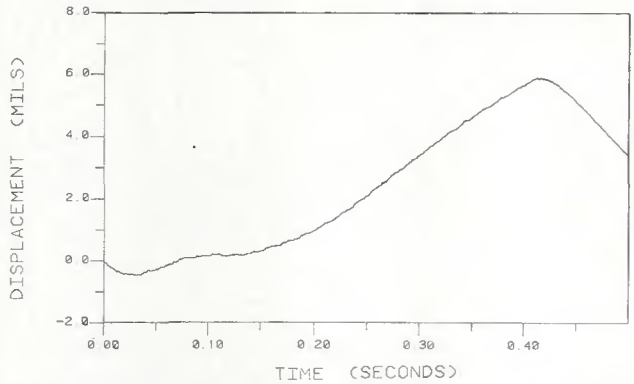

Fig. 7—Dynamic displacement curve for hot-dip galvanized steel (truncated cone electrodes, 0.22-in. nugget, 12,000 A, 24 cycles)

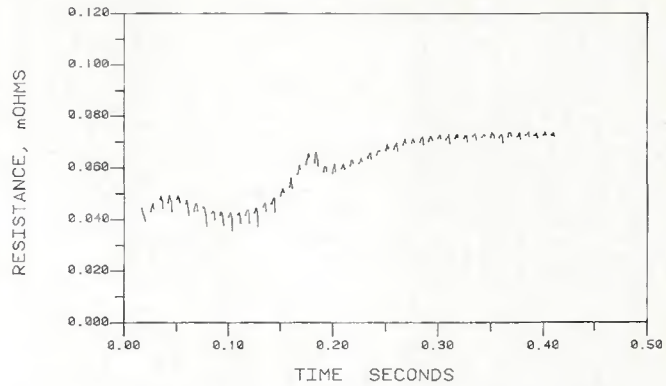

Fig. 8—Dynamic resistance curve for hot-dip galvanized steel (truncated cone, 0.22-in. nugget, 12,000 A, 24 cycles)

The four channels of data—current, voltage, displacement and force—were collected and recorded using a DEC MINC-23 minicomputer with preamplifier, analog-to-digital converter, and clock modules. This system has the capability of sampling and storing the four channels of data sequentially at rates up to 8 kHz, or 2 kHz per channel. Since most of the welding process information occurs at about 60 Hz, data collection rates of above 1 kHz per channel usually provide a good signal. The data collection was triggered by the lowering welding head, and a time-delaying circuit was incorporated to trigger the data collection toward the end of the squeeze time and just before the welding current began.

Calculation of Dynamic Resistance

One of the most interesting and relevant parameters which can be obtained from a spot weld is the dynamic resistance. This is calculated by dividing the weld voltage by the current; however, there are several different ways of doing this. Many years ago, when dynamic resistance measurements were first made, the data were stored on an oscilloscope, and the peak voltages and currents were divided. One rationale for this is that dI/dt is zero at the peak, hence the induced voltage is zero. Watney and Nagel (Ref. 26) have developed a computational method that attempts to remove the induced voltage from the voltage measured by the sensor; however, the only voltage/current pairs that may be used to calculate the resistance are still those at which dI/dt is zero. Thus, only one data point of dynamic resistance is available per half cycle. This is because the voltage and current are not true sine waves, due to the firing angle of the ignitrons (*cf.* Figs. 3 and 4). No universal correction scheme has been developed that can provide dynamic resistance data more frequently than once per half cycle. This is a serious disadvantage for any feedback control scheme using dynamic resistance.

Another problem is that there will generally be a phase shift between the welding voltage and current waveforms, and simply dividing these waveforms point by point will not yield correct results. Accurate calculations can, in principle, be obtained by dividing the maximum voltage in each half cycle by the maximum current in the corresponding half cycle. When measuring dynamic resistance with a computer, the phase shift between voltage and current must be considered. Correction for this phase shift is rarely done on commercial dynamic resistance monitors. In practice, the peaks can be difficult to locate precisely with a computer, as it only samples discrete points of data. For example, at 1 kHz per channel sampling rate, one has only eight data points per half cycle. It is possible to use very high sampling rates to more precisely locate the precise peak in the curve, although this requires much more computer memory. It is also possible to estimate the peak location from much lower data sampling rates. In this case, a curve-fitting routine can be applied by the computer. In a commercial unit, an analog device may be needed for low-cost real-time monitoring. Analog devices are less versatile than digital sampling, however, and should be used only after the voltage and current waveforms have been established for a given welding machine.

The voltage across an inductive load is related to the current by

$$V = I R + L\, dI/dt \qquad (2)$$

where R is the resistance of the load and L is the inductance. The phase shift between voltage and current is a function of R and L. If one simply assumes that the phase shift is constant throughout the weld, and corrects for it on this basis, the resulting resistance shows spurious effects. A different approach is to assume

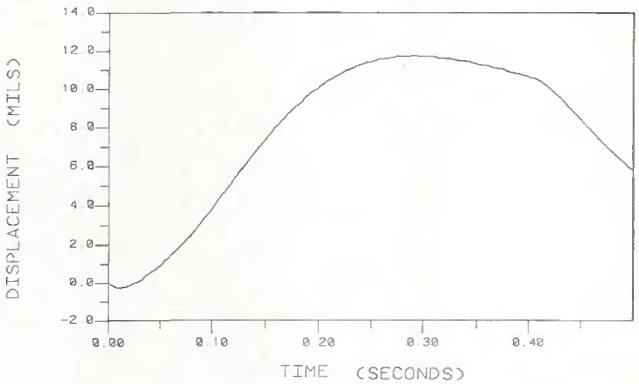

Fig. 9—Dynamic displacement curve for uncoated steel (truncated cone, 0.22-in. nugget, 8500 A, 24 cycles)

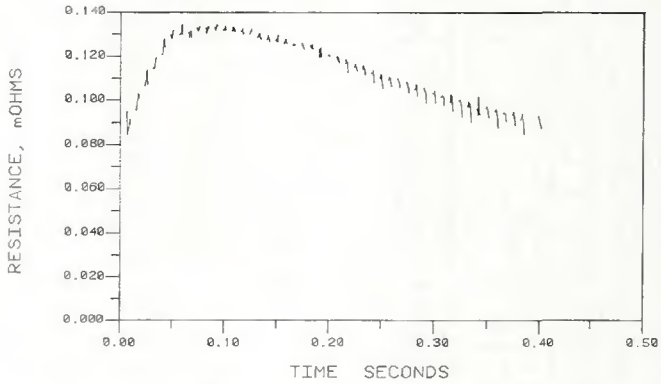

Fig. 10—Dynamic resistance curve for uncoated steel (truncated cone, 0.22-in. nugget, 8500 A, 24 cycles)

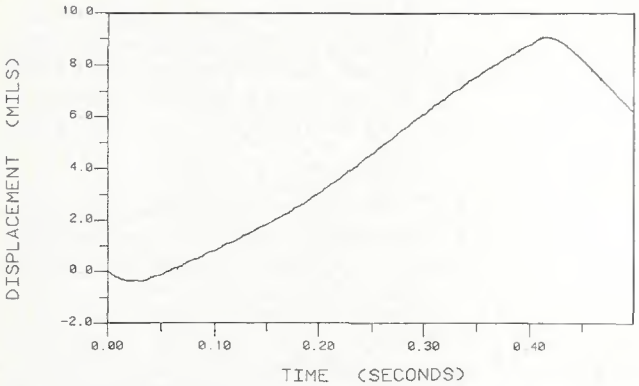

Fig. 11 — Dynamic displacement curve for galvannealed steel (truncated cone, 0.22-in. nugget, 12,800 A, 24 cycles)

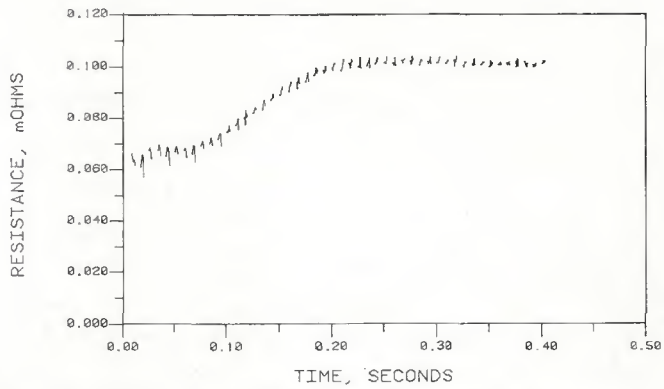

Fig. 12 — Dynamic resistance curve for galvannealed steel (truncated cone, 0.22-in. nugget, 12,800 A, 24 cycles)

that R and L are constant over two consecutive samples of data. If V, I, and dI/dt are inserted into Equation 2 for each of these data samples, the resulting system of equations can be solved for R and L. This yields better results, but still presents an undesirable degree of scatter in the resistance curve. A better approach is to assume that L is constant for a half cycle and perform a curve fit to the data for that half cycle. If this is done, and a value of L is selected for the half cycle, then a value of R can be calculated for each data point in that half cycle.

An example of the resulting dynamic resistance curve for hot-dip galvanized steel is shown in Fig. 8. In this curve, the resistance was calculated at and around the peak current and voltage, rather than only at the peaks, hence each half cycle is represented by a curved line. Fortunately, the variations in resistance from cycle to cycle are generally larger than the variations found calculating several resistances around the peak value. Although several resistance values are obtained for each half cycle by this method, it is faster computationally, and probably almost as accurate, to calculate only one resistance point per half cycle. This can be done by simply fitting all the voltage and current data in one half cycle to Equation 2, assuming both R and L to be constant over that half cycle.

Analysis of Data

Dynamic inspection information was obtained for hot-dip galvanized, galvannealed and uncoated steel sheet. This was used in conjunction with scanning electron microscopic (SEM) and energy dispersive x-ray (EDX) analysis of the developing weld nuggets to provide an explanation of the mechanisms of weld formation and growth, as well as to indicate how material variations affect the dynamic inspection data. The welding process was stopped at various stages before completion, and the faying and electrode/sheet interfaces were studied. This provided a stop-action sequence of the developing nugget. EDX analysis was used to determine the movement of the zinc and iron, as well as the location where the iron first melts and begins to form a weld. Much of this metallurgical analysis is presented elsewhere and is not repeated here (Ref. 28).

Dynamic resistance and displacement traces are presented for a hot-dip galvanized material in Figs. 7 and 8, an uncoated material in Figs. 9 and 10, and a galvannealed material in Figs. 11 and 12. The differences between these figures can be related almost exclusively to the coating differences because these three materials had identical base steel substrates. The hot-dipped coating was mostly free zinc with a very thin Fe-Zn alloy layer. The galvannealed coating was thinner and composed entirely of Fe-Zn alloys so that the coating was much harder than the hot-dipped coating.

The different phenomena occurring during nugget formation and growth, and the effect of coating type, can be illustrated by referring to the generalized dynamic resistance and displacement curves in Figs. 13 and 14.

By comparing the dynamic resistance curves in Figs. 8, 10, and 12 with the generalized resistance curve, it can be seen that the resistance curve of the uncoated material exhibits only Regions 1, 6, 7, and 8 (marked on Fig. 13). The galvannealed coating exhibits all regions except 4 and 5, and the hot-dipped coating exhibits all eight regions. From the same type of comparison among the dynamic displacement curves, it can be seen that the displacement curve of the uncoated material exhibits only Regions 1, 4, 5, and 6. Both of the galvannealed and hot-dipped coatings exhibit all six regions, although Regions 2 and 3 are not always pronounced for the galvannealed material.

Scanning electron microscopic analysis has shown that Region 1 of the resistance curve occurs due to the breakdown and fritting of insulating films. Region 2 is due primarily to bulk heating of the coating at

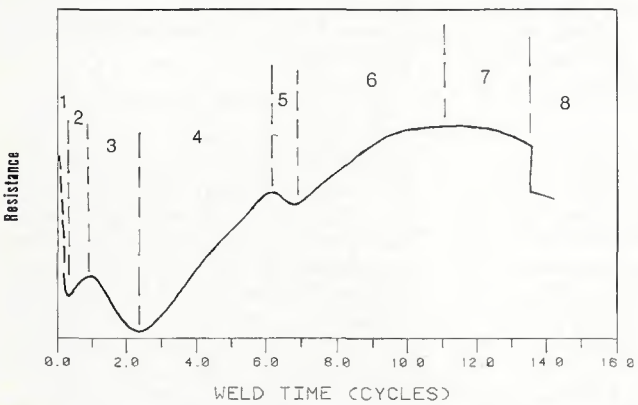

Fig. 13 — Generalized dynamic resistance curve

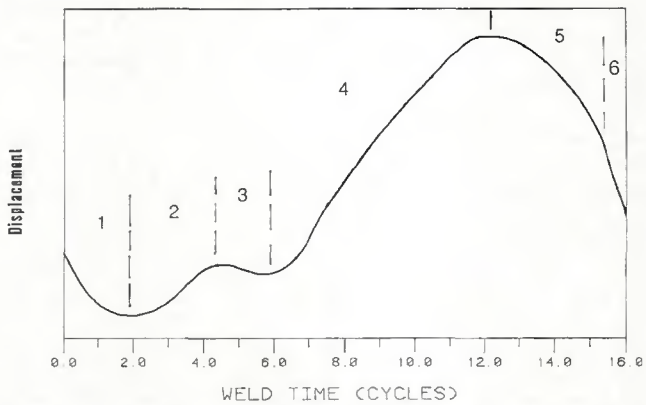

Fig. 14 — Generalized dynamic displacement curve

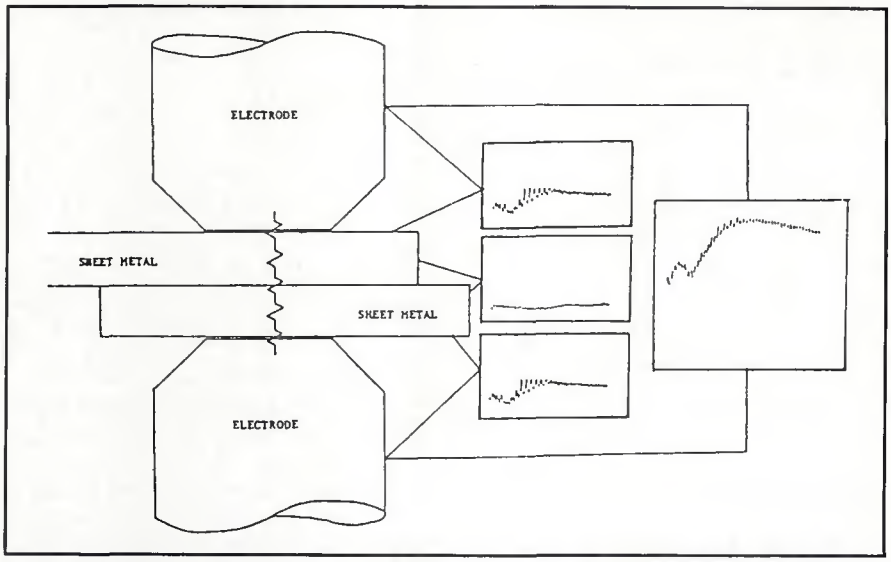

Fig. 15—Dynamic resistance curves of the faying and electrode interfaces (galvannealed steel, truncated cone, 0.22-in. nugget, 12,800 A, 24 cycles)

the electrode/sheet interfaces. Scanning electron microscopic photographs of the developing nugget show that the faying interface is molten zinc at this time, but that the coating at the electrode/sheet interface has not yet started to melt. Region 3 is due to the zinc coating becoming completely molten at all interfaces. This decreases the contact resistances to nearly zero, and the bulk temperature of the substrate is not high enough to appreciably increase the resistance. Region 4 results from the increasing bulk resistivity of the substrate as it heats up. The slight decrease in resistance in Region 5 is believed to be the result of a seal forming which constrains the soft material between the electrode tips and keeps the material from being expelled. The sudden increase in the halo of molten zinc at the faying interface and the indentation of the electrodes at the electrode/sheet interfaces at this time increases the area of current flow which decreases the resistance. Note that Region 5 does not occur for the uncoated or galvannealed materials because they do not have the soft, free-zinc coating which can so easily be pushed aside. Region 6 is the continuation of bulk resistive heating of the substrate. Region 7 is primarily due to softening of the substrate material to allow the electrodes to indent. This also increases the halo size with a resulting decrease in resistance. Region 8 occurs simultaneously with the expulsion of material from the faying interface.

The initial drop in the dynamic displacement curve in Region 1 is due to the electrode force flattening asperities slightly and bringing the sheets to be welded into contact. Materials with a zinc coating have a more pronounced valley here due to the softness of zinc. Uncoated material will start to expand almost immediately upon initiation of the current since it has no coating layers to push aside. Regions 2 and 4 are due to thermal expansion. Some of the zinc will begin to be pushed from between the electrodes so that Region 2 will have a lower slope than Region 4. Region 3 is due to rapid removal of the molten zinc coating from all of the interfaces (some slight zinc removal has been occurring during the previous region). This occurs simultaneously with Region 5 of the resistance curve and the rapid increase in halo size. Region 5 is due to substrate softening, and Region 6 is due to expulsion of some material from the faying interface.

It was found that most of the occurrences in the dynamic resistance information (*i.e.*, the "humps") were due to the electrode/sheet interfaces, rather than the faying interface. This observation is shown in Fig. 15, which presents dynamic resistance data for each interface along with the resistance from electrode to electrode. For this reason, a number of other experiments were performed on sheets with one side of the zinc stripped in order to determine more precisely the role of the different interfaces on the mechanisms of nugget formation. These results are now being prepared for publication.

A major concern evidenced from the results in Fig. 15 is that monitoring of the dynamic resistance may reflect changes at the electrode interface rather than the faying interface. Thus, the weld itself may not be undergoing inspection as much as one would otherwise expect. This needs to be further understood before an accurate quality control monitoring system for welding of galvanized steel can be developed, based on dynamic resistance. Perhaps the use of dynamic displacement would be more indicative of weld formation in a quality control scheme. The use of both sources of information is probably the best way to obtain quality assurance information.

Summary

In the preceding sections, the general methods of spot weld monitoring have been reviewed; methods and cautions for monitoring weld voltage, current, force and displacement have been described; and methods and errors in calculating dynamic resistance have been given, along with examples on several types of steel, both coated and uncoated. While dynamic resistance may not be practical as a method of monitoring the weld behavior of galvanized steel, the dynamic resistance curve and the displacement curve used together and coupled with SEM and metallurgical analysis provide useful laboratory monitors of the RSW process. This serves to reinforce the idea that monitoring of several sensors is more beneficial than using only a single RSW monitor. While dynamic resistance may not be useful in some commercial applications, it can provide useful insight into the RSW process, especially in the laboratory.

Conclusions

Accurate, repeatable and relevant quality control information can be obtained from the RSW process if the proper instrumentation and noise reduction techniques are utilized. It is seen that the dynamic electrical resistance and mechanical displacement curves provide significant information concerning nugget formation and growth in both coated and uncoated steels. The dynamic force curves are of little use at present since the inertia of the welding head reduces the response sensitivity of this monitoring technique.

It is clear from the results of this study that more information about the RSW process can be obtained by the use of multiple sensors than from any single sensor. It is felt that such multiple sensing techniques will be necessary in the future to achieve the most reliable RSW process quality control.

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