Analyzer for Nondestructive Process Control of Resistance Welding

Weld nugget expansion is correlated with current to provide in-process control of weld acceptability during the welding of titanium and aluminum

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ABSTRACT. This paper presents the results of five years of research which terminated successfully in the development of a highly reliable spotweld analyzer system for determining the condition of spotwelds in aircraft structural components. Statistical data indicate a 93 to 99% correlation between monitor signals and spotweld properties.

Investigation of monitor systems, which are based on a single response characteristic such as rate of expansion, maximum expansion, or maximum current, have a correlation range of 42 to 92%. This correlation is considered to be too low to meet the spotwelding reliability requirements for aircraft structural hardware.

The analyzer developed from this study bases the determination of spotweld properties on a minimum reading of five points taken from the expansion response curve, and a minimum of five points taken from the welding current response curve. The weld accept-reject decision is available at the end of each weld sequence. Additional monitoring of machine parameters during the weld sequence makes it possible to identify the parameter that is outside of accepted limits, and to determine what caused the weld to be unacceptable.

The use of this analyzer will not only greatly improve the reliability of spotwelded structural airplane components, but also a substantial cost and weight savings will be realized from the increased use of resistance welding.

Introduction

Full use of the resistance welding process has been restricted in the past, primarily because of inadequate process control, and also because of the lack of nondestructive testing devices to inspect each production weld. As a result, it is not uncommon to encounter premature weld joint failures, in resistance-welded equipment, and vehicles, operating under normal conditions. A method for detecting low weld-strength caused by non-uniform weld nuggets, insufficient penetration, or reduced nugget diameter, would reduce premature weld failures.

Lack of reliability in the resistance welding process can result from one or more of the following causes:

1. Inadequate preweld cleaning.
2. Misfit of parts.
3. Machine variations.
4. Machine malfunctions.
5. Utility supply variations.
6. Lack of electrode-to-part normality.
7. Incorrect machine setup.
8. Inadequate machine maintenance.
9. Improper tooling.

The causes of low reliability can be divided into two classes: those relating to equipment, and those relating to the process. Equipment inconsistencies include: machine variations, machine malfunctions, incorrect machine setup, inadequate machine maintenance, and utility supply variations. Process inconsistencies include: inadequate preweld cleaning, misfit of parts, lack of electrode-to-part normality, variations in spot spacing, short edge margin, and improper tooling.

Variations resulting from any one of these conditions directly affect spotweld properties. The result is: small or large welds, low or high strength and penetration, expulsion, forgeout, and other problems. Variations in spotweld properties also affect response signals such as secondary current, and expansion (movement in the upper electrode), taken during the weld sequence. Monitoring and recording these response signals during the weld sequence produce typical patterns and magnitudes for acceptable welds. As the welds vary from the ideal, the response signal curves change. When the change in the weld is great enough to change the response signal beyond a limit known to represent the approximate boundary between good and bad, the weld is considered unacceptable.

With this logic in mind, a process control system can be implemented that will determine when any of the equipment and process parameters have changed from predetermined values or conditions, and will thereby give a measure of spotweld quality and repeatability. Such a system can monitor, record, store logic, and indicate decisions based on signals that respond to changes in equipment and process parameters. A system that performs this function, based on the response signals from weld nugget expansion and welding current, is explained in this paper.

Approach

The initial work that led to the development of a spotweld analyzer was done on an expansion and current monitor that indicated weld acceptability based on maximum expansion. Maximum current was added later as a response signal characteristic to assist in determining weld acceptability.

The expansion monitor establishes a zero reference when the welding force has been applied to the work, and before beginning the weld interval, and records the movement of the spotwelder ram with respect to the frame of the machine during the weld interval. Calibration of this system makes it possible to read ram move-

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Paper presented at the AWS National Fall Meeting held in New Orleans, La., during Oct. 6-9, 1969.

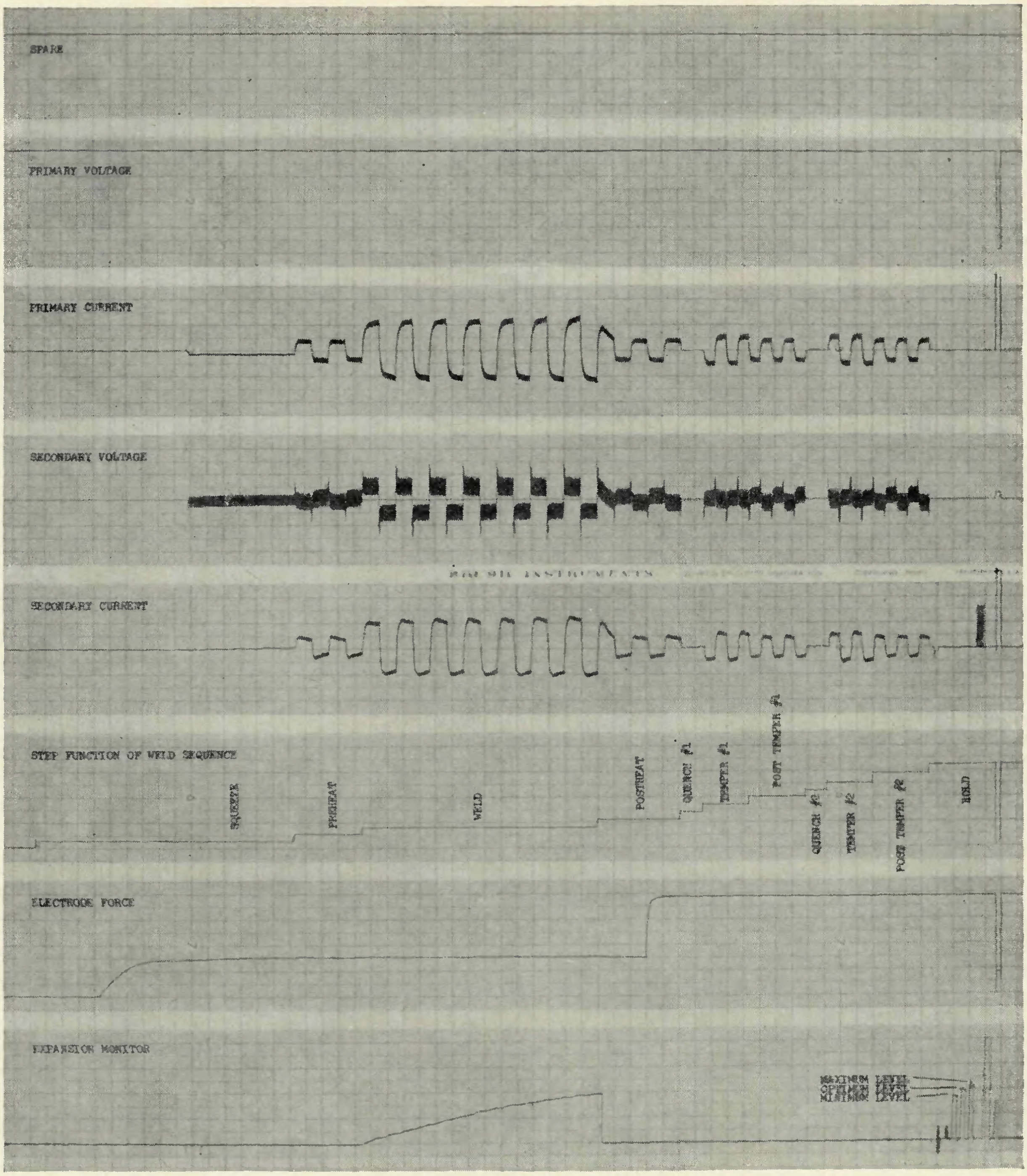

Fig. 1—Oscillographic traces of spotweld equipment parameters

ment in inches directly from the oscillograph trace.

The Manufacturing Research and Development organization of The Boeing Company has developed a system that monitors, records, analyzes, and provides a decision about weld properties from the response curves of weld nugget expansion and weld current. Provisions have also been made for adding weld force. These three response curves were chosen because they are easily monitored, and because of their sensitivity to variations in weld properties, and to each other.

The expansion monitor signal reacts to the thickness of the material between the electrodes. This thickness dimension is affected by: the thermal expansion of the metal, the ductility of the metal while it is hot (which results in indentation), removal of metal from the area between the electrodes (expulsion and forgeout), and by voids (porosity), resulting from thermal contraction. The expansion monitor is, therefore, highly responsive to changes in process parameters such as misfit, spot spacing, edge margin, electrode normality (which results in expulsion), porosity, forgeout, lack of penetration, etc. The expansion monitor also responds to changes in electrode force.

The weld current monitor is highly responsive to the equipment parameters such as transformer tap switch setting, phase shift setting, and weld force. The current monitor also shows the time at which these parameters were changed during the weld sequence. The weld current monitor is also responsive to the area of conductivity at the interface. Here, conductivity is dependent upon interface pressure (weld force), and upon the size of the nugget during its formation. The increased weld force increases current amplitude (resulting from increased interface area), but decreases magnitude of the expansion trace (resists ram movement). Regarding forge force, the time of change from weld to forge force has a substantial effect on weld quality, and often drops the expansion curve below the zero reference.

Another important function of a reliable process control is that it should be able to quickly identify the parameter that is out of limits, causing an unacceptable weld. This is accomplished by a separate system which records primary voltage, primary current, secondary voltage, machine sequence, and electrode force—Fig. 1.

Statistical Plans and Results

A number of test plans were conducted which were laid out in accordance with statistical principles. The purpose of the test plans was to determine whether or not the correlation between the response signals from expansion and current was high enough to be useful as a method of nondestructive determination of weld properties.

To prove correlation, the weld test plans were designed to change the weld properties by varying equipment and process parameters through a number of fixed levels, using a fractional factorial design. This technique produced nuggets which varied in diameter, penetration and strength; and which also contained certain defects. These changes in nugget chaaracteristics must correlate with the monitor response signals being studied, if these signals are to be useful in determining weld properties.

Some equipment and process parameters, however, can be expected to interact with each other to cancel the effect on a response curve through producing nuggets that are quite different. It has been found that most false predictions can be eliminated by analyzing a second, and sometimes a third, response signal. In addition, the occurrence of a defect (expulsion, etc.) is typically timed in a specific portion of the weld sequence. Therefore, reading only one point on a curve will provide insufficient data to completely determine weld acceptability.

The percentage of correlation in the right-hand column of Table 1, and also in Table 2, is based on a number of points taken on two response curves. Table 1 also shows the degree of correlation obtained by using a single characteristic of each response curve. The highest percentage of correlation for each weld property occurred when five points on both the expansion curve, and the current curve, were considered. Further, this chart demonstrates that secondary current correlates best with tensile shear strength, and nugget diameter, but has poor correlation with fatigue life. Expan-

Table 1—Results of Titanium Statistical Evaluation of a Factorial Test Plan to Determine the Reliability of Weld Properties

	Reliability prediction for dssignated measurements, %						
					5 Points[a]		
Weld property	Expansion rate of rise	Max. expansion	Max. current	Area under expansion curve	Expansion	Current	Expansion and current
Nugget diameter	84	67	95	62	94	97	99
Tensile shear	82	65	96	54	89	97	99
Fatigue life	42	80	52	62	95	66	97

[a] 5 points—mangitude measurements at end of 1, 3, 5, 8, & 16th impulses. Weld parameters varied in this statistical plan were weld force, weld time (impulses), weld heat, and electrode radius.

Table 2—Results[a] of Statistical Evaluation on Aluminum—Correlation between Monitor Response Curves and Weld Properties, %

	First test[b]	Second test[b]	Third test[b]
	Weld force—Forge delay—Weld heat—Current decay heat	Current decay time—Heat time—Forge force—Electrode radius	Misfit—Weld force—Weld heat—Forge force—Forge delay—Electrode radius
Tensile shear	92.3	97.9	94.2
Nugget diameter	98.21	99.84	93.7
Minimum penetration	87.42	88.99	99.0
Maximum penetration	95.65	97.08	99.1

[a] Results are based on using 6 points on both the expansion and current response curves.
[b] Weld parameters varied.

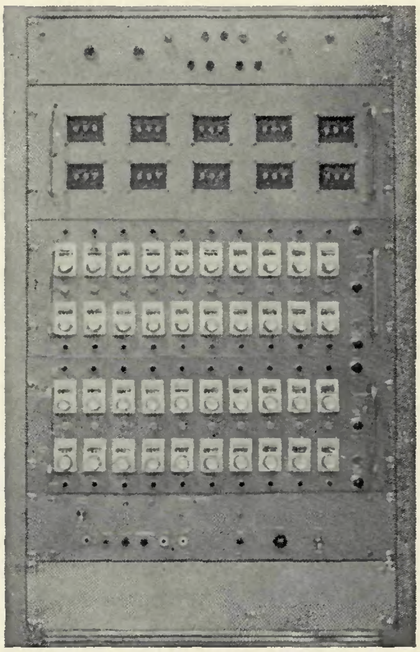

Fig. 2—Spotweld analyzer

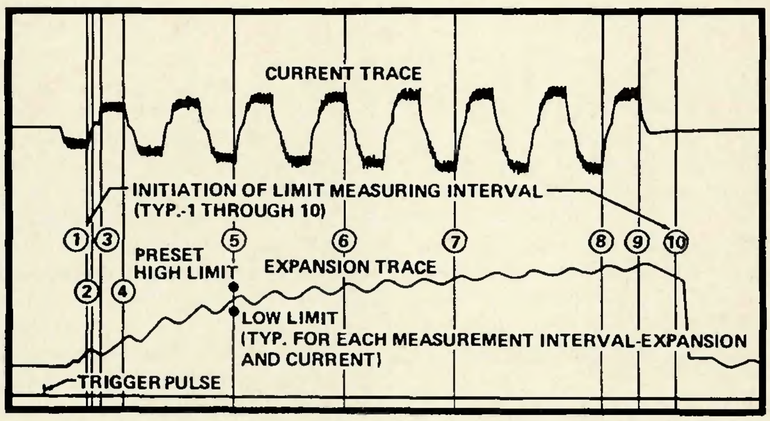

Fig. 3—Oscillograph recording of analyzer function for a conventional spotweld

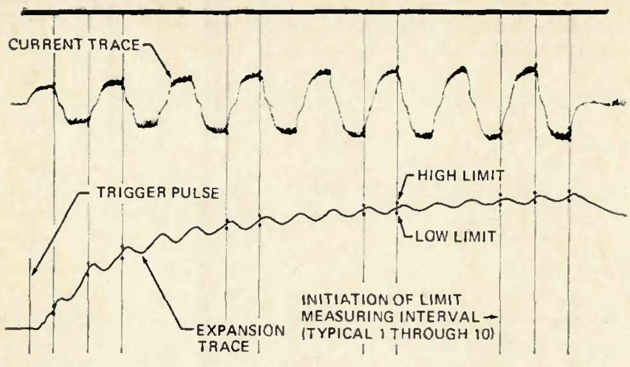

Fig. 4—Oscillograph recording of analyzer functions for a titanium spotweld detector limits set for optimum weld

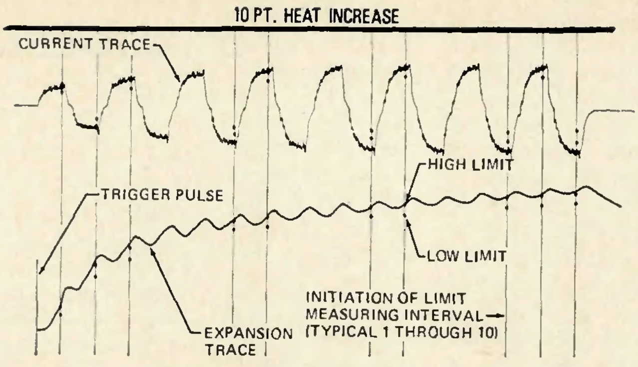

Fig. 5—Oscillograph recording of analyzer functions for a titanium spotweld; detector limits set for optimum weld—10 pt. heat increase

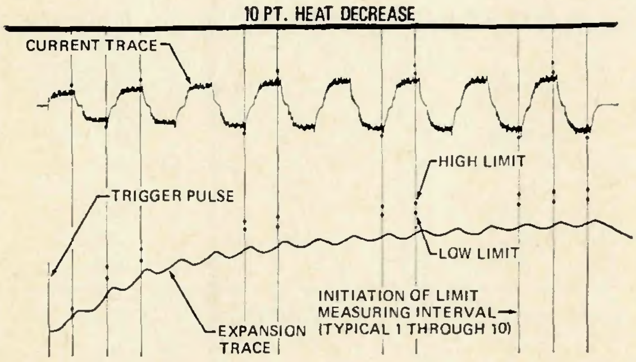

Fig. 6—Oscillograph recording of analyzer functions for a titanium spotweld; detector limits set for optimum weld—10 pt. heat increase

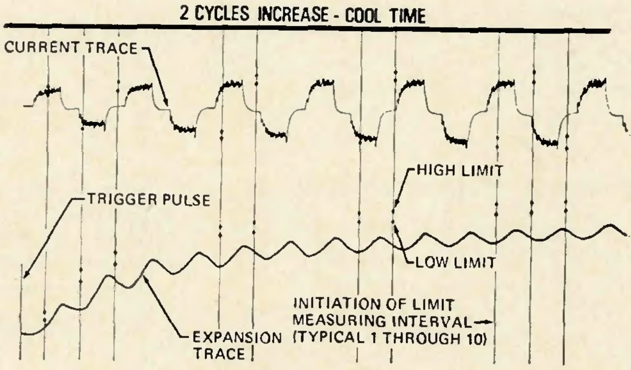

Fig. 7—Oscillograph recording of analyzer functions for a titanium spotweld detector; limits set for optimum weld—2 cycles increase—cool time

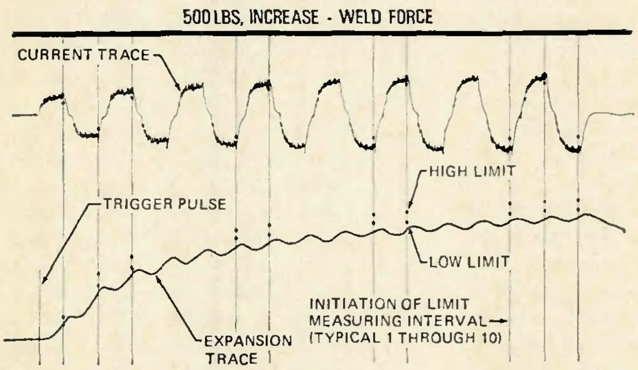

Fig. 8—Oscillograph recording of analyzer functions for a titanium spotweld detector; limits set for optimum weld—500 lb increase—weld force

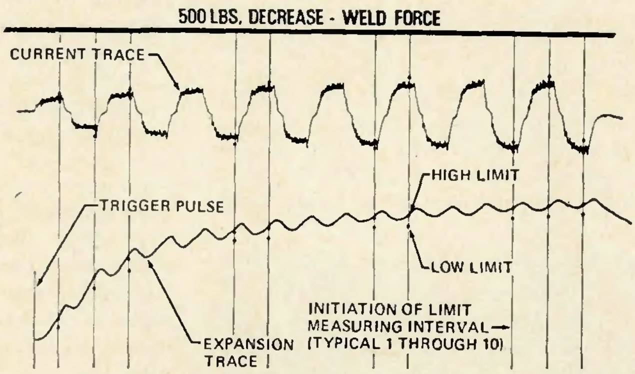

Fig. 9—Oscillograph recording of analyzer functions for a titanium spotweld detector; limits set for optimum weld—500 lb decrease—weld force

sion has the best correlation with fatigue life, but is not as good with tensile shear, and nugget diameter. Therefore, both curves are needed to cover all three weld properties and provide a correlation of 97% and over.

Statistical results have verified that correlation which is both good, and usable, is obtainable for most weld properties only when the multiple-point, two-response curve approach, is taken.

Table 2 also shows that correlation varies depending on what equipment and what process parameters are changed. Note that when misfit is a variable in the plan, variations result in both the area and in the shape of the interface contact. A further result is a wide variation in apparent nugget diameter as affected by the direction in which the weld is sectioned for metallurgical examination. The coefficient of correlation with nugget diameter, and sometimes with tensile shear strength, is low. Penetration consistency is apparently not affected, therefore, correlation remains high. Lack of interface surface pressure (misfit) also often results in expulsion, which shows on the expansion curves as a drop in this response much below the initial level.

Thus, faulty welds can be detected by noting variations in the response curves from a set standard, taken at a number of points of time during the weld sequence. These variations often relate to the welding parameter, which, because it was not within allowables, caused the weld nugget to change in some specific characteristic, and to result in a different response pattern and magnitude than the acceptable standard. The new response pattern, and the variation in magnitude, can very often be identified wth a particular machine or process problem, and is, therefore, of assistance in maintenance, and in locating problems in preparatory processes.

Analyzer Development

The statistical data previously discussed indicate that the reliability of prediction of spotweld quality is high when five or more datum points are used from both the weld current, and the nugget expansion response curves. To obtain this prediction of weld quality, it was necessary to measure five points from the expansion curve and current curve of each weld, and also to measure the macro sections. These data were then programmed into a mathematical equation, and processed by a computer.

Boeing has designed and constructed a two-channel spotweld analyzer, that will predict spotweld quality at the completion of each weld, without a computer. This analyzer monitors the response curves of weld current, and also of weld nugget expansion. The analyzer will determine whether the relative level of the response curves is below, within, or above, a minimum or maximum level setting, taken at ten points of time during the weld interval. The ten timers that initiate the level detectors are connected in cascade, and are adjustable from 0 to 999 cycles of 60 Hz line frequency.

At the end of each preset time period, a trigger pulse initiates the next cascaded timer (and the respective set of level detectors) which then operates for 200 microsec. The level detectors are calibrated to read in inches for expansion, and in amperes for current. The output of the detector circuits trigger indicator lamps that show whether the response curves were below the minimum detector setting, within limits, or above the maximum detector setting during the 200 microsec measuring period. A set of three final indicator lamps show whether all ten measurements of the respective response curves were within the set limits, or outside them.

The principal of operation of the analyzer, is to establish an envelope bounded by minimum and maximum limits for the current and expansion response curves, that will produce an acceptable weld. The analyzer detector limits are set at these respective values for ten points during the weld interval. All welds falling within this range are acceptable, and all welds falling outside this range are unacceptable.

Figure 2 is a view of the weld expansion and current analyzer. The top drawer houses the ten interval timers, the middle drawer houses the minimum and maximum expansion detector potentiometers, and the lower drawer houses the current detector potentiometers. The detector decision lamps for each curve are located at the right side of these drawers.

The two final decision lights, which denote whether the weld is acceptable or unacceptable, are located on the left side of the top panel.

Figure 3 is an oscillograph recording of a titanium spotweld showing the analyzer functions. The top trace is the current trace, and the lower trace is the expansion trace. The vertical lines numbered from one to ten represent the end of the time period of the respective interval timer. The dots above and below the expansion trace on the fifth vertical line represent the minimum and maximum settings of the fifth set of expansion detectors.

Analyzer Application

The analyzer indicates whether or not each weld was repeated with the same predetermined parameters. It also detects changes in weld force, weld current magnitude, heat and cool time, heat interval, electrode contour, line voltage, surface resistance, electrode normality, edge distance, and spot spacing.

The analyzer provides four important functions:

1. Detects incorrect machine setup.
2. Detects machine malfunctions that require maintenance.
3. Indicates process repeatability.
4. Provides a quality control record for acceptance or rejection of the part.

Six analyzer recordings (Figs. 4-9) show how changes in the welding parameters (from an optimum setting) affect the response curves of weld current, and of weld expansion. The detector settings, based on the value required to produce an acceptable weld, remain unchanged. Only the indicated welding parameter for each curve has been changed.

Conclusion

From a detailed study of the correlation which exists between expansion, secondary current, and spotweld properties, a reliable analyzer has been developed for use in the nondestructive process control of resistance spotwelding.

The spotweld analyzer technique requires that an envelope (or band) of acceptability be established for both the expansion and current response curves of each production weld. The envelope provides both the minimum and maximum limits of expansion and current, taken at established points in time during the weld sequence. If the response signals fall within designated magnitude limits, the weld is acceptable. If the response signals at any time fall outside the limits, the weld is unacceptable. The cause of an unacceptable weld is often easily deduced from the pattern of unacceptable signals obtained during the weld sequence.