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AN OVERVIEW OF ADVANCED PROCESS CONTROL IN WELDING WITHIN ERDA

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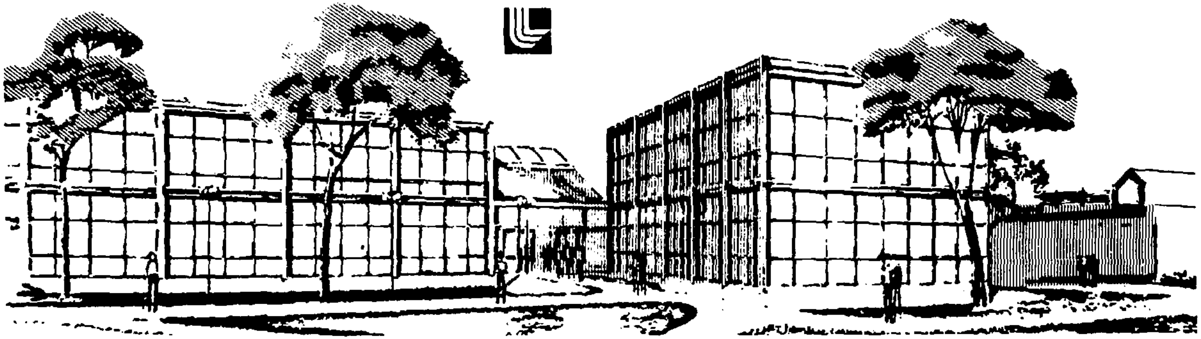

INDEX TERMS

Welding . . . .
Computers . . . .
Automatic Control . . . .
Electron Beam Welding . . . .
Joining . . . .
Quality Assurance . . . .
Production Control . . . .

AN OVERVIEW OF ADVANCED PROCESS CONTROL IN WELDING WITHIN ERDA*

ABSTRACT

The special kinds of demands placed on ERDA weapons and reactors require them to have very reliable welds. Process control is critical in achieving this reliability. ERDA has a number of advanced process control projects underway with much of the emphasis being on electron beam welding. These include projects on voltage measurement, beam-current control, beam focusing, beam spot tracking, spike suppression, and computer control. A general discussion of process control in welding is followed by specific examples of some of the advanced joining process control projects in ERDA.

INTRODUCTION

The subject is "process control." The dictionary definition of process is that it is a particular method of doing something generally involving a number of steps or operations. The definition of control is "a means of restraint, a check." Putting them together, we define process control as a means of restraining or checking each step or operation involved in doing something. Why do we need advanced process control in welding in ERDA? What's wrong with the type of control we have in other industries? If we look for a one word answer, I believe that word is reliability. I don't think that anyone can question that one of the biggest responsibilities within ERDA is maintaining high reliability, particularly in the nuclear weapons area. When we use the term "reliability" in discussing welds, we mean that the welds do everything we expect of them and, hopefully, more. We mean that the welds will neither fail under design conditions nor will they contribute to the failure of some other critical part.

I'm sure you are familiar with the reliability requirements of a nuclear plant. A major failure would be catastrophic, and a minor failure that would be insignificant in any other plant may be time consuming and expensive beyond reason. In order to prev[illegible] failure, the welds must be designed to satisfy all the requir[illegible] with a margin of safety, the material must meet all specif[illegible]ons, and the joining processes used must be developed and qualified to give a high-quality product every time. Because of [illegible]y, we depend on 100% inspection by nondestructive testing to [illegible] all the flaws in the completed welds and judge the quality of the weldment on the results of these tests. In some cases we cannot do a 100% inspection and must depend on process control.

GENERAL CONSIDERATIONS

Reliability

The reliability requirements of the weapons system are based on different criteria than the reactor system. Reactor design permits the use of large safety factors to cover any reasonable design or fabrication discontinuities.

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This assures the government and the public that even the most unlikely failure will not cause environmental damage. In weapons design we cannot afford these huge safety factors. We must approach the requirements laid down by the designers as closely as possible, or the weapon will not operate as designed. This is also reliability, but it goes beyond that of safety requirements. Efficient weapons design requires the fabrication of very precise assemblies using minimum-thickness structural materials, but at their maximum strength. Design constraints often dictate that welds possess near 100% efficiency and that they be made with a minimum heat input. The weld may be adequately strong, but is often unacceptable if it distorts too much. Some of the designs call for parts to meet dimensional requirements within tenths of a millimeter. In order to meet this requirement, we may precontour surfaces and provide extra material to compensate for weld induced permanent strain.

Many factors in the welding process affect the distortion. The fixturing is important because it may fit tighter on one part than another, withdrawing more heat and giving less shrinkage. If there is a second material under the weld, the amount of heat absorbed from the weld may depend on the closeness of this second material. If this material is closer than desired, it may physically resist the shrinkage of the weld. If this material is heat sensitive, then too deep a penetration may damage it or the welding heat may cause gases to be generated that may damage the weld being made in the overlaying material. If the heat is reduced to prevent this, then the weld may be too shallow and fail. We have the same high-quality standards and the same welding problems in obtaining strong, reliable welds that the reactor manufacturers do. We also have additional problems that are peculiar to the weapons system requirements. Factors that are not even considered in normal welding may be essential variables in the welding of weapons systems and may have a large effect on the usability of the product. Process control is critical in these cases.

Process Control

What is process control in welding? It may be as simple as telling a welder "Hey Joe, weld these parts together for me," or it may be as involved as programming a computer to control every facet of a welding process. Developing a welding process is finding the factors that affect the quality of the final weld and how closely they must be controlled to get the desired product. In this development phase, we carry out a welding experiment. We vary the factors one at a time or in combinations and determine the limits of variation permitted. We then design the process equipment to maintain each factor within these limits or tell us when any factor goes out of the limit.

What are these factors? The American Welding Society defines a weld as "a localized coalescence of metals or nonmetals produced either by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler metal."[1] In other words, for the majority of welds you apply heat to fuse the metals and you use pressure to hold them together until solid. Process control appears to be simple. All you have to do is apply the right amount of heat to the right place at the right time under the right conditions. We know how to control the production and application of heat. In gas welding the variables are gas composition, gas flow, the distance of the torch from the work, the speed of travel of the torch across the work, and the amount of cooling from the addition of filler metal. In electric processes we need to control the voltage, the amperage, the gas cover, distance of the torch to the work, and the speed of welding. In electron beam welding we determine the total power applied to the work by controlling the accelerating voltage and the beam current, and we determine the power density by controlling the spot size and the travel speed. Delivering welding heat to the right place is simpler in electric arc welding than in electron beam welding because the arc spot size is large compared to the electron beam spot size. The electron beam spot may be as small as 0.375 to 0.5 mm and an offset of 0.375 mm or so in a low-powered weld may produce an acceptable looking weld, but one with shallow penetration. Spot location on the workpiece is checked visually by the operator, so this phase of process control is manual and dependent upon the skill of the operator. Pressure plays a minor role in fusion welding, usually only to hold the parts together; while in pressure welding, flash welding, or resistance welding, it is a significant factor in the process.

Material

As I have already mentioned, we first determine the factors that must be controlled and how closely they must be controlled as the first step in process control. This looks like an easy task, but it can be very difficult. For example, we tend to think that the material meets specifications and is not a significant factor in process control. Materials are ordered to a specification that is usually written to meet the minimum requirements of the job at the lowest price. Often, no thought is given to weldability. I'm sure you're all aware of the breakup of ships during and after World War II. In this case the fault was in the high transition temperature of the material being welded and the poor design use of this material. As you know, welding got all the blame. An example of material effect on welding is the experience of W. S. Bennett at the ERDA Rocky Flats Plant of Rockwell International in trying to make a controlled-penetration gas-tungsten arc weld in a type-304 stainless-steel modified with nitrogen for strength and electro-slag remelted for cleanliness. A considerable variation, as much as 50%, was noted between plates taken from the same heat and welded at the same welding parameters. Further investigation revealed that the variation was between plates taken from the top and bottom of the ingot. It is theorized that the cause is the aluminum content, which varies from 5 ppm at the top, where penetration is the deepest, to 28 ppm at the bottom. In 1966, Glen Oyler at American Car and Foundry, Albuquerque Plant, found the same phenomenon in type-304L stainless-steel,[2] and he attributed it to the silicon content. If the silicon was high, the fluidity of the pool was excessive and this high fluidity caused reduced penetration. If silicon was low, combined with low manganese, the fluidity was too low and oxide entrapment resulted. You can see that subtle variations in the raw material can make process control very difficult.

Process control is also dependent upon cleanliness. When the results of welding are very critical, control of the cleaning process may also be critical. If the material is soiled with grease or other soils, the melting effect of the wellding heat may be changed. If the surface is heavily oxidized, it may affect the electrical characteristics, and the oxide may appear in the fusion zone or the heat-affected zone as a detrimental constituent. An example of process control is the elaborate cleaning procedure used by the aircraft industry in aluminum welding.

Human Element

Let's look at the human element in process control. You may say that the only way to control this factor is to eliminate it and replace the man with a fully automated system. Even in fully automated systems, such as resistance welding operations, the human factor is still present. Someone needs to determine when to change the resistance welding electrodes. In spite of the growth of mechanization, or automation, over 50% of industrial welding is done by manual methods, such as shielded metal arc, gas metal arc, gas tungsten arc, or gas welding. Much of the reactor welding, especially in the field, is done manually. Process control depends on the skill of the operator. While we do everything we can to help him, the final control is his. We can furnish high-quality electrodes, give him temperature measuring aids to measure the preheat and interpass temperatures, give him weld joint designs that allow him to fill the groove with the minimum of difficulty, and provide him with dependable welding power supplies. How much and the way he uses them is up to the operator and his supervision. Since there is no way of knowing when the process is out of control, the certification of the process quality must be by nondestructive methods.

ELECTRON BEAM WELDING

We are finding that the electron beam welder is being used to make the majority of the critical welds in weapons systems. This is because the high current density of the electron beam welder lets us make welds rapidly with a minimum heat input. This minimum heat input lessens distortion and the effect on adjacent materials. Since this is the equipment used for the majority of critical welds, this process is the one receiving the most attention in ERDA. Even though it is a fully electronic process and it has the usual controls and repeatability associated with electronic processes, there are several areas where control is not as good as desired. One problem is that we cannot measure the welding power parameters directly at the point where the beam intersects the workpiece. Many of the machines used for critical work are of the high voltage design and accelerating voltage is measured by passing some of this voltage through a string of resistors and measuring the current. If the resistors change in value with age, our readings become erroneous. Another problem is that the voltage reading is made at a point in the power supply tank and is not a true measure of the accelerating voltage actually applied to the electrons leaving the gun.

Voltage Measurement

Ray Dixon, of the ERDA Rocky Flats Plant of Rockwell International, has done a very nice piece of work in measuring the x-ray spectrum generated by an electron beam striking a tungsten target and then using the high-energy cutoff (short wave-length cutoff) value to calculate the voltage of the beam.[3] He found that the difference between the actual voltage of the beam when it strikes the workpiece and the meter reading could be as great as 5%. His technique is too slow to be used as a method of control, but it can be used to calibrate the welder and therefore can be considered to be a part of process control.

Beam Current Control

The beam current of the triode gun on our high voltage machine is controlled by the application of a bias voltage to the gun. This beam current is not measured directly, but is the sum of all the currents flowing from the workpiece back to the power supply. A check on the efficiency of the current measuring system can be made by passing the beam into a Faraday cup, measuring the total number of electrons in the beam, and comparing this current with the meter current. This is a good measure of the beam in a static condition, but the dynamic condition that occurs during welding is different. The beam current is lessened by secondary emission of electrons from the workpiece, and the beam is also affected by ion streams that flow up the beam back to the cathode. We have tried to measure the beam current in the beam directly by using sensitive current coils around the beam, but to no avail.

Our present method of setting the beam current to the desired value is to absorb the beam electrons in a tungsten target block and adjust the gun bias voltage until the meter reads the desired value. This meter reads the current flowing from the target block back into the system. There is no feedback control, the only control we have is the control of the circuit that maintains the bias voltage at the set value. However, a fast beam current control has been developed and used in Germany and is available as an accessory. This system uses a bias voltage control that is located in the high-voltage tank adjacent to the bias power supply. The beam current in the gun is monitored and compared with the beam current desired. A signal to adjust the bias voltage is sent through a light pipe into the high voltage tank to the bias control by means of a LED transmitter and a photo transistor.

Compliance is better than 1% of the set value, and it is claimed that the response time of the unit is so fast that beam current ripple is essentially eliminated for current levels above 1 mA. This unit has a true feedback control and we are waiting for delivery of a unit to see if the performance is as advertised.

The Union Carbide Y-12 plant is establishing a facility that will demonstrate advances in the state-of-the-art of vacuum electron beam welding. A high voltage welder is being designed and built that will use specially designed and built equipment and circuits where commercially available equipment is not adequate. This unit should be ready for test very shortly. The power supply is a solid-state, fast response supply guaranteed to have less than 1% output noise and instability over the entire output range. A fast response beam current control is incorporated with a 0.001% load regulation and a response time of less than 500 μs. A complete new control system has been designed and the entire operation will be controllable by computer. When the equipment is operating as designed, it is expected to be a significant advance in process control of electron beam welding.

Focusing

In electron beam welding, the accelerating voltage and the effective beam current determine the amount of heat applied to the work. The focusing coil controls the size of the beam as it hits the work and the resulting spot size determines the power density at the workpiece. The power density is the factor that really determines the type of weld. If we operate a 7.5-kW welder at 3.6 kW or 120 kV and 30 mA and focus the beam to a diameter of 0.5 mm (0.020 in.) on the workpiece, we have a power density of 18 000 W/mm^2, or 11 500 000 W/in.^{2}. If we increase the spot size to 0.76 mm (0.030 in.), we reduce the power density to approximately 7 935 W/mm^2, or 5 100 000 W/in.^{2}. A further increase in spot size diameter to 1 mm (0.040 in.) gives us only 2 830 W/mm^2 or 2 900 000 W/in.^{2}. This drastic change in power density can give equally great changes in weld characteristics. Since the best method we have at present of determining sharp focus is to focus the beam on a tungsten target and visually determine when the spot size is the smallest, the possibility of getting a spot size a few thousandths larger or smaller than sharp focus can be purely a matter of judgment. Once the spot size is set, it is the function of the welder electronic lens supply to maintain the focus coil at the same field intensity. The lens coil controls the beam size by opposing the effect of the space charge between the electrons, which pushes them apart.

Focus Point Measurement – We have found in critical welds, especially ones made with low power, that a special method of measuring the beam is quite useful. A technique was developed by A. Sanderson of the Welding Institute to measure the beam by passing a 0.12 or 0.3 mm diameter tungsten wire through the beam at approximately 88 m·s and displaying the beam current signal from the wire on an oscilloscope.[4] The output display is a Gaussian curve and the area under the curve is a measure of the beam power, the average width of the curve envelope is a measure of the beam width, and the height of the trace a measure of the focus condition. Since the flying wire technique requires a spinning arm and considerable space in the welding chamber, we have modified the deflection system on our welder and use a flying beam instead. We can sweep the beam across a stationary tungsten wire at various speeds, turning off the pickup circuit on the return sweep so that we do not get a double trace, and we can vary the time between sweeps to allow the wire to cool down. When we finish our development work and have the machine set to make the weld we want, we sweep across the signal wire and photograph the oscilloscope trace for record. When we are ready to do a critical production part, we set the machine according to the previous schedule and take a photograph of the new oscilloscope trace. If the traces are similar, we make the weld. If they are not, we investigate to find why the machine has apparently changed. If we can't find the reason, we make more samples and adjust the parameters until we get the desired weld and then take another trace photograph for record. When we do this, we assure ourselves that the machine is operating properly. Unfortunately, we have not found a way to continuously monitor the beam during the welding operation, but we are still trying.

Effect of Vacuum on Focus – An external factor that affects the focus is the ion stream that moves up the electron beam to the cathode. The ions tend to neutralize the space charge between the electrons and thus increase the effect of the focusing coil. Brandon, at the Union Carbide Y-12 Plant at Oak Ridge, Tennessee, found that the quality of vacuum in the chamber had a significant effect upon the focus point of the beam because of the increased ion formation at higher pressures.[5] He found that it required approximately 5% more focus coil current to obtain sharp focus in a vacuum of 6.7×10^{-3} Pa (5×10^{-5} Torr) than in a vacuum of only 1.3×10^{-3} Pa (1×10^{-4} Torr). He found that the sensitivity of the focus point was greatest at 75 kV and decreased as the voltage went either up or down and that the same effect was noted with beam current, with the maximum being at 8 mA at 100 kV. Tests were made comparing the effect of this focus variation on penetration, and he found that the variation in beam focus resulting from typical changes in the welding chamber pressure are sufficient to affect the penetration of the welds being made. Low-energy, partial-penetration welds in low-density metals, such as aluminum, are the most susceptible. Average penetration variations in excess of 20% may occur. At the low powers, the neutralization of the space charge by the ions allow a smaller diameter spot to be formed with an increase in power density and greater penetration. It is apparent that in a precise weld where exact penetration must be maintained, process control must include the control of the chamber pressure. This can be done by mounting an auxiliary bleed line to the chamber and lowering the pressure to a selected value before starting the weld. We have also tried to monitor the pressure at the weld pool, but without success.

Beam Spot Tracking

Another problem in electron beam welding comes from the fact that the beam spot is usually very small and the body of the weld under the nailhead is also small. This means that the beam must be placed exactly on the seam and stay there. It is difficult to tell visually if the joint is fully welded or if only the top is fused. Sometimes a scribe line is placed parallel to the joint just outside the weld area and used as a reference to measure from in order to see if the center of the weld is over the joint.

George McFarland of LLL came up with the original idea for a solution to this problem and did the original development work. The work was then sent to the Union Carbide Y-12 Plant for further development. A television camera with a silicon target vidicon to look at the beam spot on the workpiece, a television monitor, and a digital readout interpreter are used. The television monitor screen is approximately 152.4 mm × 152.4 mm (6 in. × 6 in.) and approximately 6.35 mm (1/4 in.) of the weld seam is viewed. Appropriate filters and lenses adjust the magnification and the light level to usable values. In operation, the sensor in the television camera produces a voltage that is proportional to the light intensity on the workpiece. This voltage is transmitted to the television monitor to produce the picture and also to the digital readout interpreter. This interpreter has a two-level amplifier, which transforms the video signal into either all black or all white information. Approximately 350 clock pulses occur during each of the 262.5 line scans of the television camera. When the welding electron-beam spot is energized and the camera scans the first line across the spot, the number of clock pulses occurring between the zero time reference and the edge of the spot are counted. The number of clock pulses to traverse the spot are counted, the number divided by two and added to the first count to determine the position of the center of the weld spot with reference to the zero time reference. During the second line scan, the number of clock pulses occurring between the zero time reference and the center of the seam are counted in the same manner as for the weld spot. The dark line caused by illumination of the weld joint seam is sensed.

These two counts are compared and used to determine the location of the spot. This information can be used to operate indicating lights, make a record on a strip chart, or provide information to a computer, which adjusts either the beam or the workpiece to bring the two into alignment.

This system has worked and has proved to be feasible, but it is not a process control item because of several difficulties yet to be resolved. These difficulties center around the problem of obtaining a good signal from the weld seam. A tightly butted weld seam is almost impossible to see; a groove of about 0.5 mm is required on the weld seam for observation. Variation of light reflection from the surface of the workpiece causes a serious problem, especially in combination with a tight weld seam, because we need a bright background to distinguish the dark seam. These problems have not yet been solved, and I am mentioning this process in the hope that it may stimulate your thinking. Work is being done on an improved optical system under a subcontract to Y-12.

Spike Suppression

Another development, which is being pursued by the ERDA laboratories, is the use of an x-ray detector to suppress spike formation in electron-beam welds. The root of a high-power-density partial-penetration electron beam weld is not smooth, but is very jagged with a number of deep spikes. Research done at ERDA laboratories shows that this uneveness in the root is caused by the instability of the weld pool. The beam vaporizes the metal when it strikes it, creating a cavity. The depth of this cavity is determined by the energy input. The side walls of the cavity are molten and the cavity is maintained by the vapor pressure in the cavity pushing against the molten side walls. Instabilities in the side walls, accompanied by instabilities in the vapor pressure, cause the molten side wall to collapse periodically, sliding down and closing the cavity. When closure occurs, the beam energy is dissipated on the molten metal; when closure does not occur, the beam energy is concentrated on the metal at the root, vaporizing this metal and leaving a hole.

Under a contract from Y-12, graduate students at Ohio State University under the direction of Dr. Edward R. Funk evolved a method of controlling spiking. They monitor the x rays produced when the beam strikes the workpiece and use this signal to turn the beam off when the point of x-ray production reaches a certain depth.[6] Completed detection and control equipment has been delivered to Y-12 for further simplification and refinement for testing on a production system.

The process operates as follows: An x-ray detector is mounted in a lead case with a collimating slit and positioned above the workpiece to monitor x-rays produced when the beam strikes the bottom of the cavity. The detection system consists of a sodium iodide crystal, which converts high energy x-radiation to visible light. This light strikes a photomultiplier tube, which sends a signal to a driver, which actuates an infrared light-emitting diode. This signal is passed into the high voltage tank through a polymethyl methacrylate rod to a sensing photodiode in the tank, which turns the beam off for the duration of the signal. When the beam is shut off, no x-rays are generated and the beam is turned back on again. This interruption stops the beam excursion that causes the spike and the immediate turning back on of the beam prevents a void in the weld. This cycle is repeated approximately 2000 times a second to produce a spike-free weld. This technique can also be used to control the depth of penetration in a weld. One of the difficulties, however, is that the maximum depth of penetration detectable is limited by the characteristics of the material being welded, especially its opacity to x-rays. This development work was performed on aluminum, which passes x-rays very easily. The maximum depth of penetration obtained at Ohio State University in aluminum with a 3-kW machine was about 10.5 mm (0.421 in.). Further work must be done to determine the maximum depth of penetration in other materials.

Computer and Microprocessor Control

Computerization of electron beam welders is the field that shows the most promise and the one attracting the most attention in the ERDA weapons complex. The Y-12 plant has been working with computers for several years and is using computers to control cold wire feed mechanisms, to obtain welder performance data at high speed, and to control general welding parameters. A development welder has been equipped with computer control of welding parameters with feedback control. Experience gained from the use of this system will be utilized in the computer control of production welders.

Currently, the largest use of computers on electron beam welders is for high-speed data acquisition and pre-programmed control without a feedback loop. The Rocky Flats plant has several data acquisition units using either computers or microprocessors. They are in the process of equipping several additional electron beam, gas tungsten arc, and gas metal arc welding installations with high speed data acquisition units. A gas tungsten arc welder installation having a computer with a feedback loop for control is being developed. One problem has been starting the arc. Conventional high frequency starting does not start the arc within the same length of time after initiation and, if the high-frequency voltage leaks back into the computer circuit, it can destroy the computer components. An indirectly heated electrode torch has been developed that gives a predictable start without the use of high frequency and this development has helped the project considerably. Another gas tungsten arc installation has been equipped with a microprocessor to sequence all the welding functions in the process of making multiple-pass pipe-like welds on special components. The microprocessor will control all the functions by a preprogram and not by a feedback loop.

The use of computers for high-speed data acquisition is very important for several reasons. It gives a detailed record of the values of all parameters during welding with special attention to any excursions and provides an accurate quality control record of the part. It shows how closely the parameters were controlled and this record can be used to determine what parameters must be controlled and how closely. The Los Alamos Scientific Laboratory has just completed a microprocessor controlled data acquisition system on their laboratory welder and Hugh Casey is to explain this system in detail in a paper to be given at this session.

The big problem in computerization is with the transducers that send the signal to the computer. This is where the advances need to be made. The electron beam welder is a complex electronic unit operating at high power, and the normal signals coming from the measuring points are so full of transients and noise that it is difficult to determine the true signal. On data acquisition installations to date, the signals may be so heavily damped to remove this clutter that there is a real danger of losing the true excursions that are indications of minor malfunctions that may be affecting the weld. This damping is probably just acceptable in data acquisition, but it does not give a good basis for control. The problems I mentioned earlier of measuring true accelerating voltage and beam current at the point of impingment of the beam are significant here because a control computer must operate on a true signal. This is the phase we will be working on at LLL as soon as we receive the new fast beam current control that I described earlier. When we get this control, we intend to use the computer to record and analyze all the measurable outputs during a weld. We will then try to correlate the results of the weld with parameter changes and try to determine what parameters must be controlled and within what limits in order to get a reliable, reproducible weld.

BRAZING TEMPERATURE CONTROL

Let me digress from welding and describe advanced process control of a brazing operation. The success of this operation is largely due to the adiabatic surface thermometer, developed by Gerry Ditbenner at LLL.[7] This thermometer uses a differential thermocouple and heater to measure surface temperatures without heat flow, thus eliminating the large errors caused by conduction losses that are common to conventional spring-loaded thermocouples. An adiabatic type of thermocouple with a maximum temperature limit of 530°C has been on the market for several years, but it is designed for intermittent use in air and is not suitable for continuous temperature measurements in vacuum. The new thermocouple probe can measure temperatures up to 1300°C, is manufactured from materials suitable for high-temperature high-vacuum service, and is designed for continuous service in vacuum. Temperatures in air or vacuum are measured with an error at 800°C of less than 5%.

This thermocouple was developed in the automation of one of the vacuum production brazing processes at Rocky Flats. The brittle weakness of the joint is a function of the amount of beryllium-copper intermetallic formed at the interface of the beryllium and the copper-silver braze alloy. The brittleness and the width of the intermetallic layer both increase with the brazing temperature and the part temperature must be held at 804°C to obtain the maximum strength and still pass nondestructive testing inspection. The production brazing process involves local induction heating of the braze area in a vacuum chamber. In the improved process, an MCS-8 microprocessor precisely controls the power input to the induction coil. It uses the output signal from the thermocouple probe that monitors the part temperature immediately adjacent to the joint to control automatically the entire time-temperature cycle of the brazing process. The rejection rate has been greatly reduced since this computer controlled process, using the surface thermometer for feedback control, has been in use.

ARC WELDING MONITOR

The last item I am going to discuss is a digital welding parameter monitor for shop use developed by C. C. Wristen of Allis Chalmers.[8] As I remarked earlier, much of the reactor welding is still done manually, using gas tungsten arc, gas metal arc, shielded metal arc, and submerged arc welding. The normal meters used to measure amperage and voltage in shops do not have sufficient precision because of arc length changes during welding. Because they fluctuate rapidly, an estimate of the midpoint must be made, and the operator needs another person to read the meters while he is welding. The meters that have been selected for the monitor are digital because this type is easy to read, they have the accuracy required, and are more rugged than mechanical meters. They are enclosed in a sealed metal case for greater protection from the shop environment. The voltage meter has a resolution of 0.1 V and an accuracy of ±1% of the reading and can cover a range of 5 to 75 V. The current meter has a resolution of 1 A and an accuracy of ±1% of reading and can measure amperages over the range of 50 to 1000 A. Since instantaneous voltage or amperage is actually meaningless in manual welding because of the rapid excursions, the welder really wants to know the average current and voltage. The monitor contains an averaging circuit that computes the average arc voltage or current over a selected time. Selected times can be 3, 7, 11, or 15 s. The monitor also contains a memory circuit, which enables the operator to measure his own parameters. The memory is activated from a remote pendant, which the operator holds in one hand while manually welding. It displays the desired information on the digital meters and retains the readings until the pendant control is again activated. In addition to the circuit that reads and computes the average voltage and current, the monitor also contains a circuit that permits connecting a type K thermocouple and using it to measure preheat and interpass temperatures of the work and display the values on the current meter. This monitor is a very useful instrument for improving the product control of manual welding and can be used to make a permanent record for quality control surveillance.

CONCLUSION

The preceding examples of joining process control are indicative of the degree of sophistication and the strong committment to high reliability in those systems that are under the guidance and direction of ERDA's responsible nuclear weapons design and production groups. I have not had time to mention all the techniques that are being used and there are others that are still in the planning stage. This paper has covered the most significant techniques used to obtain greater reliability in ERDA systems.

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