Suppression of Spiking in Partial Penetration EB Welding with Feedback Control

Spiking can be suppressed by pulsing the beam with a feedback control system energized by a solid state x-ray detector

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ABSTRACT. A study was made of two possible methods of suppressing the spiking phenomena in partial penetration electron beam welds. The first method utilizes a unique feedback system which controls the beam current by monitoring the x-radiation produced with the beam's interaction with the workpiece. The results show that spiking can be suppressed in partial penetration electron beam welds made on the aluminum alloy, Al 7075. The feedback system utilizes a side-viewing scintillation detection system coupled to a unique pulsing system which was designed and installed in the electron beam welding machine used for experimental purposes. The second method, which used fixed frequencies in the range of 100-1000 Hz with fixed duty cycles (beam off times in the range of 150-200 microseconds), indicates that for these pulsing parameters spiking cannot be suppressed.

Introduction

Electron beam welds have many desirable characteristics when compared to welds made using conventional welding processes. Among these desirable features are the characteristic large depth-to-width ratios and the relatively low heat input per unit length of weld. There are several undesirable characteristics that are associated with electron beam welds. These include defects such as porosity, cold shuts (incomplete fusion), cracking and spiking. Porosity, cold shuts and cracking are well known defects that can be found in almost all types of welds under certain conditions. The spiking defect, however, is found only in partial penetration electron beam welds. Spiking is the nonuniform penetration of the weld which is characterized by jagged acicular projections or "spikes" which have an irregular occurrence and a nonuniform size.

All of the above defects, especially spiking, are caused by the penetration mechanism and the resulting weld geometry that are characteristic of an electron beam as it penetrates into a material. This penetration mechanism has been the subject of much research activity. Tong (Ref. 1), Weber (Ref. 2), Mara (Ref. 3), and Hashimoto and Matsuda (Ref. 4) have made the most notable contribution on this subject due to their extensive experimental work. Most of these researchers are in agreement on the basic penetration mechanism of an electron beam in a material.

What they have observed is simply that the electron beam oscillates up and down along the vertical axis of the cavity which it generates during a welding operation. It has been postulated that the electron beam oscillates in the weld cavity because of cavity closures of molten metal which intersect the beam at various heights along the vertical axis of the weld cavity. These closures result from the dynamic fluid forces of the liquid and vaporized metal atoms which are constantly in an unbalanced state. This closure mechanism which causes the electron beam to oscillate operates in a somewhat sporadic manner. It has been hypothesized that because of these irregular and unpredictable closure events the electron beam is allowed to work at the rest of the weld cavity for varying periods of time. This results in spiking which is characterized by the uneven root appearance of the weld. Clearly, the occurrence of spiking does not allow a maximum strength partial penetration weld to be made in a material.

Extensive research has been done by Armstrong (Ref. 5), Sandstrom (Ref. 6), and others, in recent years in an attempt to eliminate spiking through the judicious control and selection of welding parameters, i.e., accelerating potential, beam current, and focus coil current (to control the position of the focal point). These researchers have concluded, however, that spiking is an inherent ill that is characteristic of the high-energy-density electron beam process.

As a result of their research with x-ray movies taken of electron beam welds during the welding operation, both Weber and Mara concluded that spiking might be eliminated if the electron beam was interrupted or pulsed so as to allow it enough time to penetrate to certain levels. The suggestion offered by Mara on pulsing the beam at certain frequencies defined the starting point of this research activity. In addition, the authors felt that a feedback system which would pulse the beam on and off in an attempt to maintain a fixed level of penetration would provide a more suitable solution to the spiking problem.

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To do this, a feedback system was designed to monitor the beam current in accordance with the radiation intensity produced at a fixed level of beam penetration. A solid state x-ray detector measures the x-ray intensity produced by the penetrating beam at a certain fixed level. A high x-ray intensity causes the feedback system to turn the beam off while a low x-ray intensity causes the feedback system to turn the beam back on. By controlling the beam in this manner, this closed loop system has successfully suppressed spiking during the welding of the aluminum alloy, Al 7075.

Experimental Procedure

The feedback system which was designed for this experimental work consisted of two component systems; the detection system and the pulsing system. This feedback system was designed to be an integral part of the Hamilton Standard 3kW (150 kV, 20 mA) electron beam welding machine (Model No. W1-0) used for the experimental work. The detection system responds to the beam's penetration in the workpiece as indicated by the generated x-rays and provides an appropriate output signal to the pulsing system. The pulsing system then turns the beam on and off so as to maintain a relatively fixed level of penetration. A schematic of the feedback system is shown in Fig. 1.

The detection system which constitutes the x-ray sensing part of the feedback system is pictured on the left side of Fig. 1. The detector consists of a thallium-activated sodium iodide, NaI (Tl), scintillating crystal coupled to a type 931-A photomultiplier tube. The active area of the sodium iodide crystal is controlled by two lead collimators with apertures of 1 mm in diameter. These collimators have their apertures aligned to expose a small area of the NaI(Tl) crystal to the level at which penetration is to be controlled in the weld specimen. For experimental purposes the detector was aligned so as to be perpendicular to the direction of the penetrating electron beam.

During a welding operation when the electron beam is penetrating through the material above the level at which the detector is focused there is only a small intensity of x-radiation that reaches the NaI(Tl) crystal surface. When the electron beam reaches the level at which the crystal is directed or focused the x-ray intensity received at the crystal surface increases abruptly. It is this sudden change in x-ray intensity that turns the electron beam off to prevent further penetration. Obviously, when the electron beam is turned off x-rays are no longer produced at the focused level of the detector. The corresponding x-ray intensity at the NaI(Tl) crystal surface is decreased and the electron beam is switched back on. In this manner the detector system coupled to the pulsing system utilizes the x-radiation intensity sensed at a certain level to switch the beam on and off to maintain a spike-suppressed weld root.

The detector head of the detection system is physically a single unit that is mounted in the welding chamber adjacent to the experimental weld coupon. Figure 2 shows the detector head with the outer ⅛ in. thick lead shield and the inner housing removed. A cross-sectional view of the detector head is sketched in Fig. 3. The crystal used for experimental purposes was a Model 2D2 thallium-activated sodium iodide crystal obtained from the Harshaw Chemical Co. of

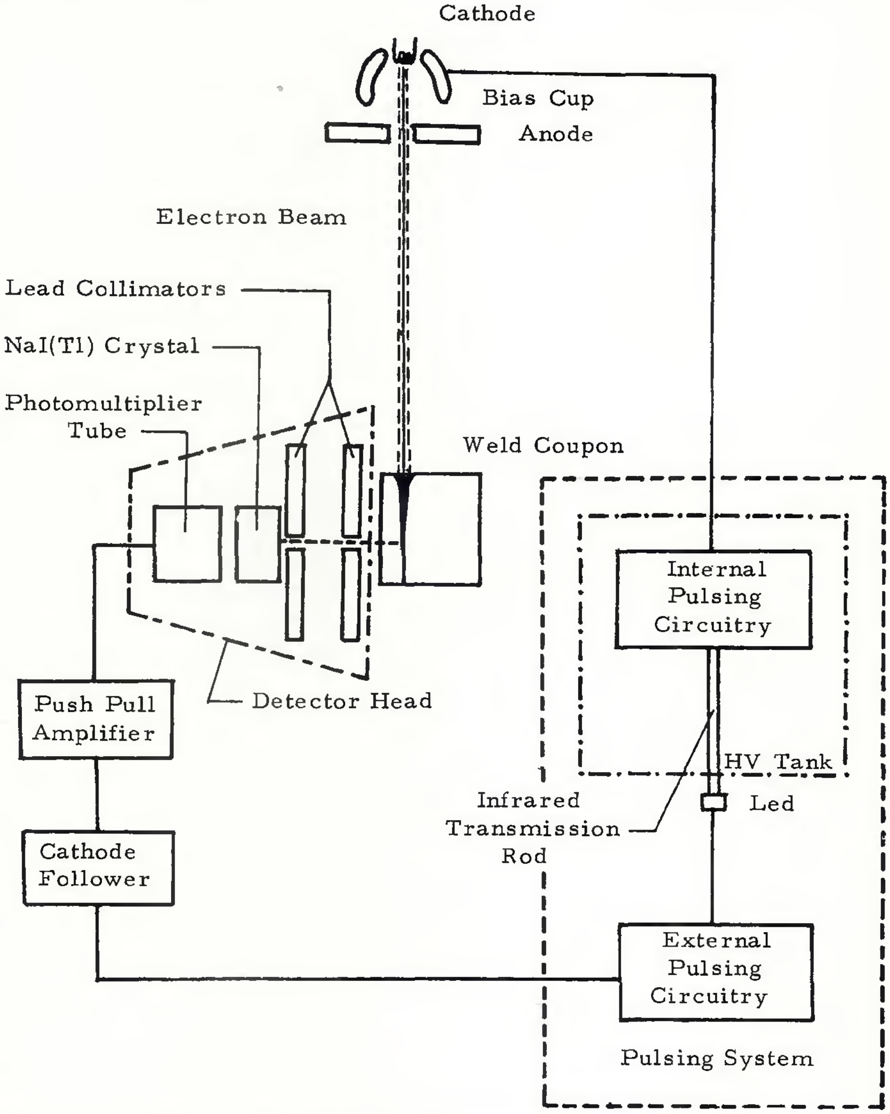

Fig. 1 — Schematic of the feedback system used to pulse the electron beam

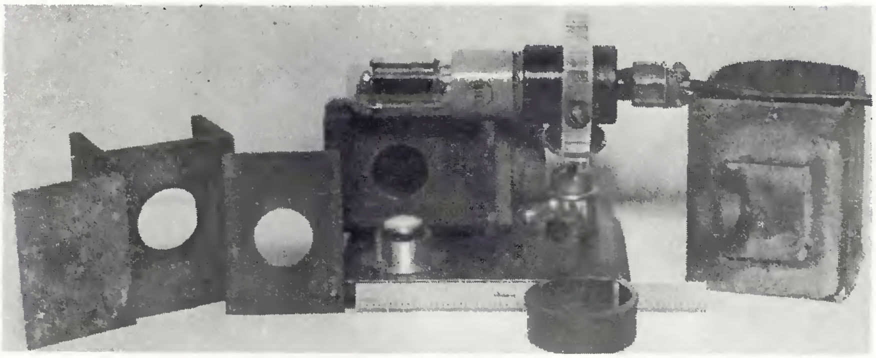

Fig. 2 — Detector head with lead shield and inner housing removed

Cleveland, Ohio. This crystal acts as an energy transducer which converts a high energy photon input (with a minimum wavelength of approximately 0.1 angstrom for 126 kVp x-rays) to a low energy photon output (visible light with a peak emission at 4200 angstroms. The photomultiplier tube used is a VT5 (RCA type 931-A) tube. This is a relatively common type of photomultiplier tube which is used in many kinds of light sensing instruments. This photomultiplier tube and the electronic circuitry to which it is coupled is an Aminco Photomultiplier Microphotometer made by the American Instrument Co., Inc., of Silver Spring, Maryland. The maximum output signal from this detector system is 7.5 V. The push-pull amplifier and the cathode follower shown in Fig. 1 are the basic electronic components of the photomultiplier circuitry.

The pulsing system as shown on the right side of Fig. 1 consists of internal and external electronic circuits that are coupled by a plastic rod that transmits infrared pulse signals. A schematic of the pulsing system is shown in Fig. 4. The input signal to the pulsing system from the detection system turns the infrared LED (GE SSL-35) on and off in accordance with the penetration of the electron beam in the workpiece. This infrared signal is transmitted from the external circuitry to the internal circuitry by means of a polymethyl methacrylate rod. The ⅛ in. rod provides high voltage isolation of the internal circuitry in addition to allowing infrared signal transmission. Figure 5 is a sketch of this infrared transmission fixture. The polymethyl methacrylate rod used was purchased from the Cadillac Plastic Company of Kalamazoo, Michigan.

The internal pulsing circuitry shown in the lower half of Fig. 4 varies the potential on the bias cup (located in the gun column of the welding machine) in response to the infrared signal that it receives. When the bias cup potential is decreased (more negative) the beam is turned off and when it is increased the beam is turned on.

The feedback system as described works in the following manner. In order for the system to respond, the electron beam must first penetrate to the focused level of the detector. Then, providing that attenuation losses are not too great (due to the interaction with the aluminum weld coupon) and that a sufficient area of the detector is exposed (proper aperture size of the lead collimators) the sodium iodide crystal scintillates in response to the incident x-radiation. These photons of visible light generated by the NaI(Tl) crystal are detected by the photomultiplier tube. The photomultiplier tube and its chain of amplifiers produces a positive output signal which serves as the input signal to the pulsing system. This positive signal turns the LED on which causes the internal pulsing circuitry to decrease (more negative) the bias cup potential which turns the beam off by stopping the flow of electrons. When the x-radiation intensity decreases to zero the output of the detector is zero or near zero. The LED is turned off, the bias potential is increased (less negative) and the beam current is turned back on until the

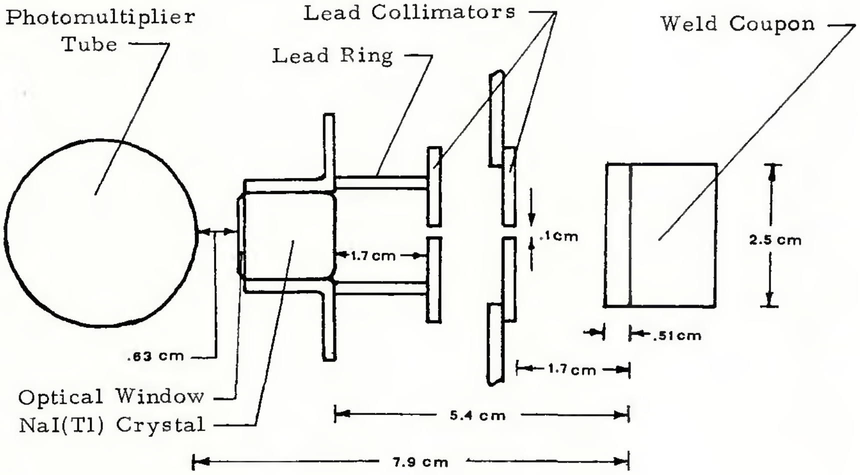

Fig. 3 — Cross section of detector head

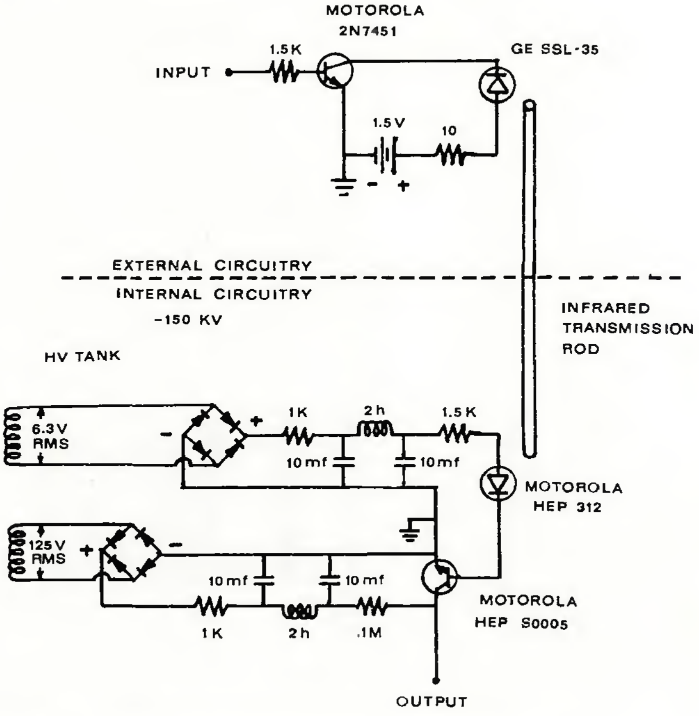

Fig. 4 — Details of the pulsing system indicated in Fig. 1

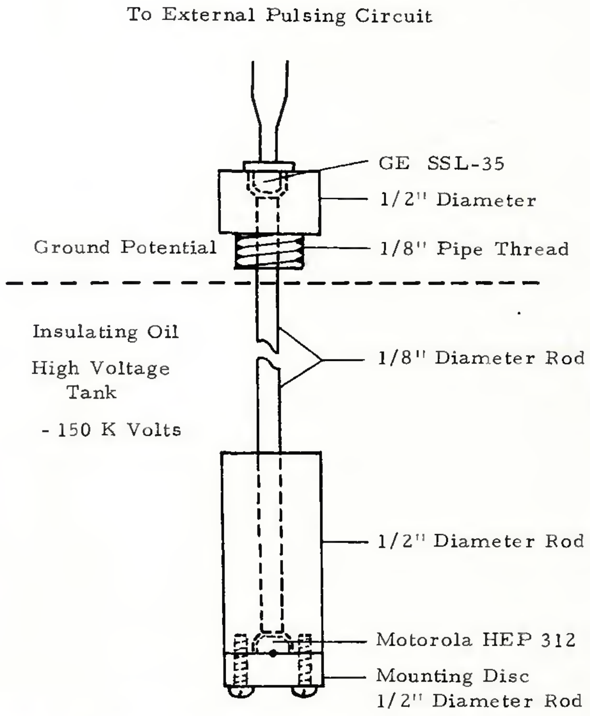

Fig. 5 — Infrared transmission fixture

beam again penetrates to the focused level of the detector at which time the above shut-off sequence is repeated.

All of the experimental runs were made in the aluminum alloy, Al 7075. This popular structural alloy of aluminum was chosen because spiking is readily obtained when electron beam welding this material. In addition, the average spike length is significantly larger than that obtained in other aluminum alloys (e.g., Al 6061, Al 2024, and pure aluminum, Al 1100). A cross-sectional view of a weld coupon is shown in Fig. 3. The break-apart sandwiched weld coupons which were 2 in. in length were used so that the longitudinal weld root could be examined without any postweld metallographic preparation.

Experimental Results

Most of the experimental welds were made at 126 kV, 7mA, 21 ipm, and using a finely focused (surface focus) beam of approximately 10 mils in diameter. Table 1 shows the machine parameters and the operating conditions for each of the experimental runs. As can be seen from the data, most of the experimental runs were made using the same machine parameters. This was purposely done to determine the reproducibility of the results obtained with the new feedback system.

The beam current was monitored by measuring the voltage fluctuations across a ten ohm resistor which connected the insulated work (using a sheet of mica) to ground. This voltage was fed into a cathode ray oscilloscope for instantaneous readout. By studying these voltage patterns (proportional to the beam current) on the scope the proper beam current for the suppression of spiking was determined. Typical CRT display waveforms of the beam current are illustrated in Fig. 6. As labeled in the figure, sketch #1 is the CRT trace obtained when the beam is off. Sketch #2 is the resulting trace when the beam is turned on and no feedback is used. The third, fourth and fifth illustrations represent the three possible modes of operation when feedback is used. Sketch #3 is observed on the scope when the beam current value is too small. Specimens welded under this condition showed that the beam had not penetrated uniformly to the focused level of the detector. Spiking was present above the focused level of the detector for these runs. The waveform illustrated in sketch #5 resulted when the beam current value was too high. The resulting welds made under this condition exhibited normal spiking. The square waveform pictured in sketch #4 indicated that the proper beam current value was being used for a given penetration level to suppress spiking. It should be noted that this square waveform could be maintained only within the range of approximately 6.5 mA to 7.5 mA. These current readings are only arbitrary values, however, since they were measured with the dc ammeter on the welding machine.

The resulting period of the above waveforms was approximately 250 microseconds with close to a 50% duty cycle. Thus, the feedback system turned the electron beam on for 125 microseconds and off for 125 microseconds in an attempt to control the beam's penetration.

In order to provide a means of correlation and analysis of the welded specimens four variables were measured and recorded from each specimen. These penetration variables are similar to those used by C. W. Weidner and L. E. Shuler (Ref. 7). P_{max} is the maximum penetration of a spike while P_{min} is the minimum depth of penetratration in a weld. ΔP is the difference between P_{max} and P_{min} and $\%\Delta P/P_{min}$ is a factor which defines the variation in penetration of the weld. Thus, $\%\Delta P/P_{max}$ is defined as the penetration variation factor. P_{min} was used in this ratio rather than P_{ave} since P_{ave} would have to be weighted towards the P_{min} value for most welds. This P_{ave} value would be a function of spike width, spike length, and spike frequency. Most of these values can at best only be approximated, whereas, P_{max} and P_{min} can be measured to a relatively high degree of accuracy. A quick glance at P_{max}, P_{min} and $\%\Delta P/P_{min}$ will let an investigator know instantly what penetration is being obtained in a partial penetration weld and with what degree of variation. Spikes obtained at the beginning and end of the weld were not included in the analysis. Each weld was given approximately 1/10 in. to reach a steady-state condition before experimental parameters were measured. The above parameters for each run are given in customary and metric units in Tables 2 and 3, respectively.

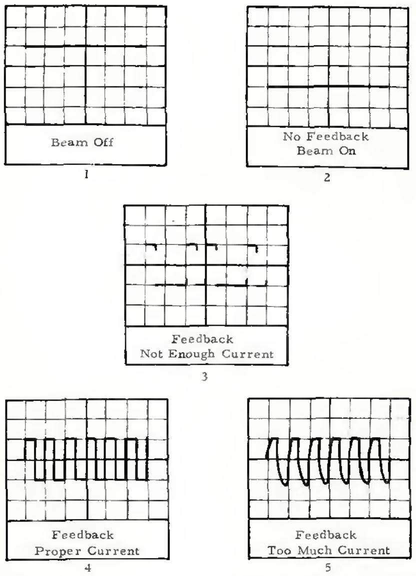

Fig. 6 — Typical CRT display waveforms of the beam current

Table 1 — Experimental Operating Parameters

Specimen	kV	mA[(a)]	Travel ipm	Control
1	126	7	21	Feedback
2	126	7	21	Feedback
4	126	7	21	Feedback, current too low on first weld
8	126	7	21	Feedback
9	126	7	21	No feedback
12	126	7	21	Feedback
13	126	7.5	21	Feedback, current too high
14	126	7	21	Feedback
15	126	7	21	Feedback
16	126	7	21	Feedback 60Hz transverse deflection of beam
18	126	7	21	Feedback

(a) These beam current values are arbitrary since they were measured using a dc ammeter.

Table 2 — Feedback Controlled Weld Data (Customary Units)

Specimen	P_{max}, in.	P_{min}, in.	ΔP, in.	$\%\Delta P/P_{min}$	Spikes/ in.
1	.311	.267	.044	16.5	—
2	.274	.235	.039	16.6	90
3	.292	.266	.026	9.8	116
4	.280	.259	.021	8.1	66,85
8	.299	.257	.042	16.4	86
9	.306	.199	.107	53.8	74
10	.285	.247	:038	15.4	84
11	.261	.226	.035	15.5	82
12	.302	.276	.026	9.4	90
13	.344	.265	.079	29.8	70
14	.307	.274	.033	12.1	96
15	.289	.263	.026	9.9	86
16	.372	.321	.051	15.9	72
17	.305	.273	.032	11.7	—
18	.320	.284	.036	12.7	62
19	.425	.315	.110	34.9	57

Table 3 — Feedback Controlled Weld Data (Metric Units)

Specimen	P_{max}, cm	P_{min}, cm	ΔP, cm	$\%\Delta P/P_{min}$	Spikes/ cm
1	.790	.678	.112	16.5	—
2	.696	.597	.099	16.6	35.4
3	.742	.676	.066	9.8	45.7
4	.711	.658	.053	8.1	26,33.5
8	.759	.653	.107	16.4	33.9
9	.777	.505	.272	53.8	29.2
10	.724	.627	.097	15.4	33.1
11	.663	.574	.089	15.5	32.3
12	.767	.701	.066	9.4	35.4
13	.874	.673	.201	29.8	27.6
14	.780	.696	.084	12.1	37.8
15	.734	.668	.066	9.9	33.9
16	.945	.815	.130	15.9	28.4
17	.775	.693	.081	11.7	—
18	.813	.721	.091	12.7	24.4
19	1.08	.800	.279	34.9	– 22.4

Discussion

The results show that spike-suppressed welds were made in experimental Runs #1, 2, 12, 14, 15 and 18, of which Figs. 7 and 8 are typical. The remaining runs illustrate anomalies that deserve special attention. The first is Run #4 (Fig. 9) which has two welds. The weld on the left was made with only 5 mA and as can be seen from the photograph it has normal spiking. The beam does not penetrate, however, beyond the control level as defined by the spike-suppressed weld on the right which was made with a 7 mA beam current. Run #8 (Fig. 10) which has several small spikes was made after a new filament was installed. It appears that the feedback system is only slightly, if at all, dependent on the filament size (worn filament vs new filament). As can be seen from later runs, possible effects

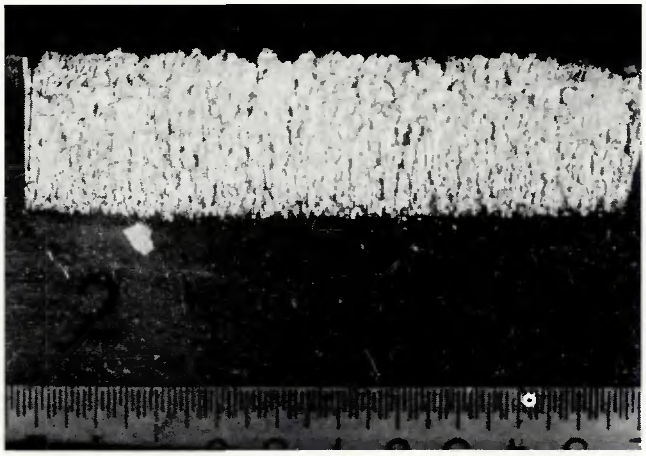

Fig. 7 — Spike-suppressed weld of Run #2 made in Al 7075 at 126kV, 7mA (arbitrary), 21 ipm travel speed (surface focus). X5.72, reduced 46% (scale markings 0.01 in.)

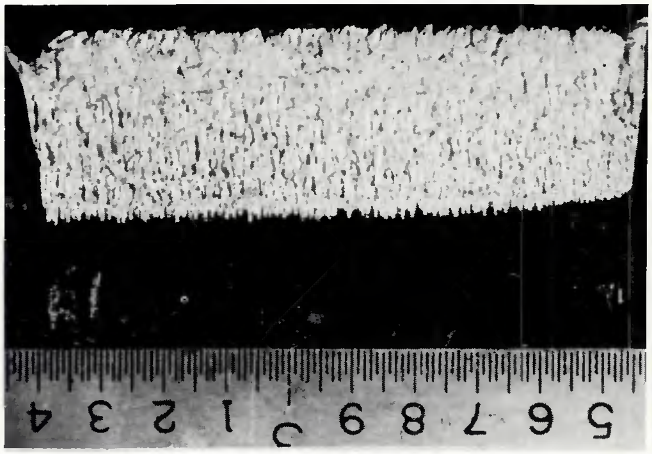

Fig. 8 — Spike-suppressed weld of Run #12 made in Al 7075 at 126kV, 7mA (arbitrary), 21 ipm travel speed (surface focus). X6.0, reduced 46% (scale markings 0.01 in.)

Fig. 9 — Two welds of Run #4 made in Al 7075. Weld at left was made at 5mA (arbitrary). Weld at right was made at 126kV, 7mA, 21 ipm travel speed (surface focus). X4.58, reduced 46% (scale markings 0.01 in.)

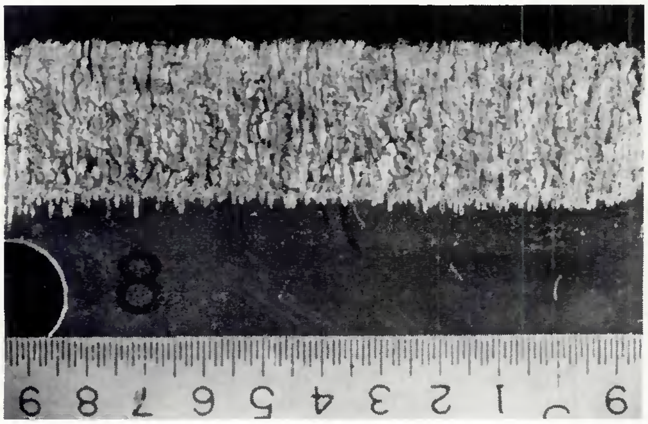

Fig. 10 — Run #8 in Al 7075 made after installation of new filament at 126kV, 7mA (arbitrary), 21 ipm travel speed (surface focus). X5.63, reduced 46% (scale markings 0.01 in.)

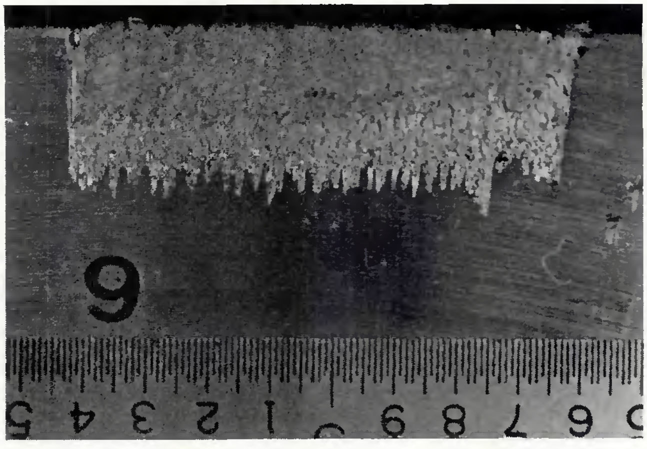

Fig. 11 — Run #9 in Al 7075 made to show spiking obtained without feedback control; 126 kV, 7mA (arbitrary), 21 ipm travel speed (surface focus). X5.94, reduced 46% (scale markings 0.01 in.)

Fig. 12 — Run #13 in Al 7075 showing increased spiking due to increased beam current; 126kV, 7.5mA (arbitrary), 21 ipm travel speed (surface focus). X6.0, reduced 46% (scale markings 0.01 in.)

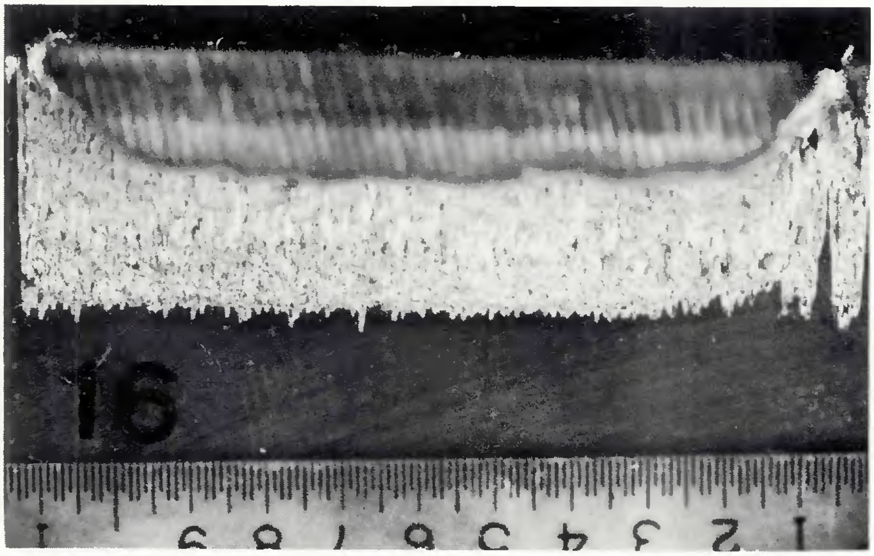

Fig. 13 — Run #16 in Al 7075 made with feedback control and 60 Hz transverse oscillation; 126kV, 7mA (arbitrary), 21 ipm travel speed (surface focus), X5.63, reduced 30% (scale markings 0.01 in.)

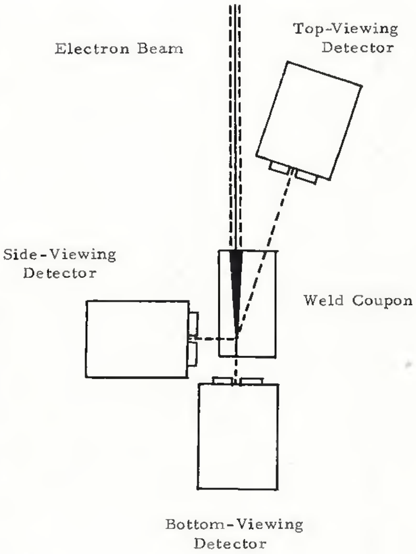

Fig. 14 — Three viewing positions for detector head

due to a filament change are only short-lived. Run #9 (Fig. 11) was made as a reference run to show the degree of spiking obtained with no feedback control used. Run #13 (Fig. 12) shows increased spiking as a result of the beam current, 7.5 mA, being slightly too large. Since the beam current was turned completely off every time it reached the focused level of the detector, it was found that a relatively weak bond was produced between the two sections of each specimen. Run #16 (Fig. 13) shows a feedback controlled weld made using a 60 Hz transverse oscillation of the beam to increase the width of the fusion zone, reduce porosity, and produce a resulting weld of acceptable strength. It should be noted that this problem may cause trouble only in low-powered electron beam welding machines which utilize small currents and which have correspondingly narrow fusion zones.

The results show that spiking can be effectively suppressed through the use of a side-viewing detector. Unfortunately, the side-viewing system has only limited use in welding applications due to the physical shape and size of various welded structures. Seldom, if ever, is there a joint of the same dimension and geometry as the one used for the weld coupons. Clearly, if a feedback system is to find general application in electron beam welding, then the detector will have to be used in a bottom-viewing or top-viewing position as shown in Fig. 14.

In addition to the side-viewing system, the feasibility of a bottom-viewing system was studied. X-ray movies were taken simultaneously from the side-viewing position and from the bottom-viewing position. Figure 15 shows a set of these x-ray films. It should be noted that the points of maximum penetration on the side view correspond to bright dots and dashes on the bottom view (these are prints taken of the x-ray film which was Kodak No-Screen high-speed medical x-ray film). The timing dots numbered on each film segment are 50 milliseconds apart. These results show that a bottom-viewing detector could be used with the present feedback system with some modification to control spiking. The authors also feel that further research work will lead to the development of a top-viewing feedback control system which will be able to be applied to most electron beam welding applications for the control of spiking.

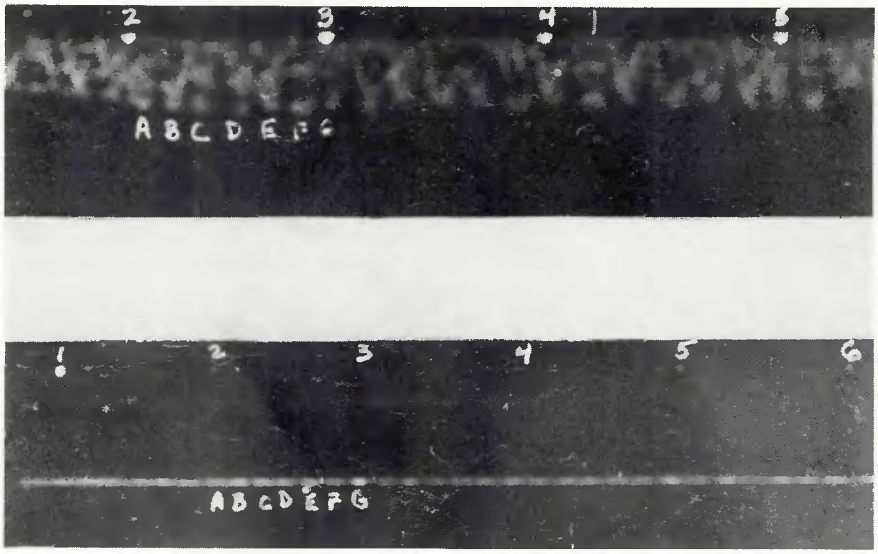

Fig. 15 — X-ray moving pictures of Run #1 taken simultaneously from side (top view) and bottom (bottom view) viewing positions. Points of maximum penetration seen from the side (A-G) correspond to bright spots (A-G) on bottom. Timing dots are 50 msec apart

In addition to this study made on feedback-controlled electron beam welding, a preliminary study was made using selected frequencies and duty cycles to pulse the beam in an attempt to suppress spiking. Initial results showed that pulsing with frequencies in the range of 100 Hz to 1000 Hz with high duty cycles (beam off times on the order of 150-200 microseconds) did not suppress spiking in partial penetration electron beam welds. The authors feel, however, that further work should be attempted using this pulsing system since it would be far easier to use than the feedback system with the detector. The machine operator would simply select a pulsing schedule characteristic of a given material and weld it. No detector positioning or monitoring would be necessary.

Conclusions

As a result of the experimental work completed, several conclusions can be made that pertain to the control of spiking and penetration in partial penetration electron beam welds.

1. The x-radiation produced by an electron beam as it interacts with the work material can be monitored from a side-viewing position and used as a feedback signal to control the beam current to effectively suppress spiking in partial penetration electron beam welds made in the aluminum alloy, Al 7075.
2. Using the feedback current control system, the penetration variation factor, $\% \Delta P/P_{min}$, ranged from 8.1 to 16.6%. When the feedback system was not used or when it was not used at the proper operating parameters the penetration variation factor ranged from 29.8 to 53.8%.
3. Experimental studies made indicate that a bottom-viewing detector can be used to monitor the x-radiation produced by the electron beam to provide a feedback signal to control the beam current to effectively suppress spiking in partial penetration electron beam welds.
4. Pulsing the beam in the frequency range of 100 Hz to 1000 Hz with high duty cycles (beam off times of 150-200 microseconds) does not suppress spiking in the resulting welds.

Recommendations

There are several recommendations which should be considered for further study.

1. Further experimental work should be done by pulsing the beam at fixed frequencies and duty cycles. A system of this type which does not utilize feedback circuitry would be far more desirable, provided feedback quality welds can be produced.
2. An attempt should be made to pulse the beam on and off at approximately 4000 Hz using a 50% duty cycle. These parameters correspond to those observed on the oscilloscope during a feedback-controlled operation on Al 7075.
3. Additional side-view feedback-controlled runs should be made on other materials to determine the degree to which spiking can potentially be controlled in each material.
4. Control of spiking should be attempted using a bottom-viewing detector to monitor the x-radiation. The present detector system will have to be modified so that it does not turn the beam off until the x-ray intensity reaches a certain level.
5. Solid state canned-type detectors should be tried for control purposes. Because of their small size geometric constraints which limit the use of the present detector would be greatly reduced.
6. In addition to a bottom-viewing detector, developmental work should be done on a top-viewing detector. A detector of this type would control the beam current in such a manner that the beam current would be directly proportional to the x-ray intensity being monitored. Thus, the beam current would be turned off or down when the x-ray intensity was attenuated to a certain level. Of the three detector positions described in this article, the top-viewing system has the most potential for the control of spiking in all partial penetration electron beam welds.

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