# Multipass Electron Beam Welding For Controlled Penetration

## Partial penetration electron beam welds with a minimum penetration of 75% of the plate thickness in a 360 mil thick plate can be obtained utilizing multipass electron beam welding methods

BY E. H. BRADBURN, R. A. HUBER, AND P. W. TURNER

### Introduction

Some manufactured items require partial-penetration welds made with low-energy inputs to prevent thermal damage at the backside of the joint. For example, it is often desirable to protect surface finishes, or it is mandatory that combustible or heat-sensitive members of weldments be kept relatively cool. With its low-energy input capability, the electron beam welding process has become a primary method for making welds on structures that, for design purposes, must not be heated to temperatures that result in marring the backside of joints or in thermal damage to adjacent members.

One problem encountered with partial-penetration, electron beam welds is a phenomenon referred to as "spiking."[1, 2] This term relates to the uneven penetration, illustrated in Fig. 1, that characterizes sharply focused, high-power-density, electron beam welds having a high depth-to-width ratio. Spiking is postulated by many investigators to be the result of "gas focusing" of the electron beam within the weld cavity coupled with hydrodynamic forces in the molten weld pool.[2, 3] Spiking is not observed in joints welded with full penetration because the electron beam does not terminate within the workpiece.

The shape of the root of partial-penetration welds depends upon the power density of the welding beam. The power density of the electron beam is mainly influenced by focusing conditions.[2] The root of a weld made utilizing a sharply focused (high-power density) electron beam terminates as a sharp, spiked edge. Spikes ranging in magnitude from 10 to 30% of the minimum penetration are not uncommon. Consequently, it is difficult to obtain as much as 75% minimum penetration without puncturing through and causing damage on the root side of the joint.

Two approaches for solving the spiking problem could be considered. One is to determine the cause by examining the numerous variables associated with materials in vacua and with electron beam generating equipment. This approach involves a study of elemental particle behavior including electrical and magnetic phenomena. The other and more practical approach proposed by the authors assumes that spiking is inherent in the process and cannot be eliminated unless conditions are altered to provide a root penetration profile with a large radius of curvature. This approach requires the development of joint designs and welding parameters that are compatible with the electron beam welding process capability. It makes use of the experimental evidence that welds having blunt or rounded-root profiles have the most stable penetration profiles. The experimental work was based on the latter approach.

### Objective

The objective of this investigation was to develop a method for obtaining

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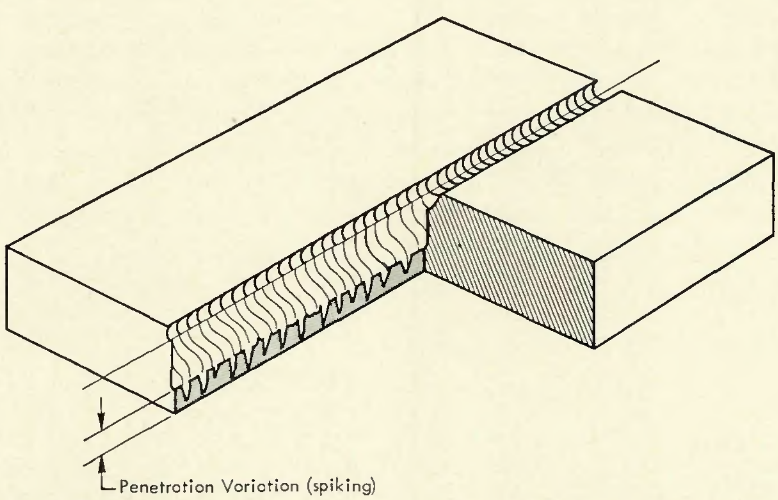



Fig. 1—Spiking or penetration variation typical of partial-penetration electron beam weld made with a sharply focused beam

**Table 1—Typical Mechanical Properties and Chemical Analysis of Uranium ¾ Weight Percent Titanium Alloy Plate**

| | Base metal[a] | Transverse weld |
|---|---|---|
| Tensile strength, psi | 144,300 | 145,200 |
| Yield strength, 0.2% offset, psi | 71,250 | 77,800 to 111,000 |
| Elongation, in 2 in., % | 10.0 | 1.5 |
| Reduction in area, % | 7.5 | 4.0 |
| Young's modulus, psi | $23 \times 10^6$ | |

[a] Titanium—0.65–0.85 weight %; residual elements—0.05 weight %; remainder uranium.

a partial-penetration electron beam weld of 75-85% of the plate thickness without experiencing a melt through (spike through) or excessive thermal effects at the underside of the weldment. The plate thickness was selected such that the minimum specified penetration (75-85% thickness) was within the range in which spike through normally occurred when the same partial penetration was attempted with a single electron beam welding pass.

## Materials and Equipment

This investigation was performed utilizing uranium 3/4 weight % titanium alloy plates that were nominally 360 mils thick. Typical mechanical properties and the chemical composition for this material are contained in Table 1.

A high-voltage, electron beam welding machine capable of delivering a maximum of 6 kw (40 ma and 150 kv) was used throughout this test program.

Partial-penetration welds were fractured for examination of the penetration profile using the test fixture described schematically in Fig. 2. A portable hydraulic ram was utilized for fracturing the weld sections.

## Procedure

Immediately prior to welding, test plates with the joint geometries shown in Fig. 3 were electropolished in a solution comprised of orthophosphoric acid saturated with chromic acid anhydride. Current density and polishing times were nominally 9 amp per sq in. and 25 sec. Polished parts were rinsed in water and dried with acetone. The plates were clamped in a hold-down fixture grooved along the center and were welded with varying parameters. Butt joints, machined to various groove designs, were evaluated to determine the optimum joint geometry. These joints were welded with filler metal, with filler-metal inserts, and autogenously. The welds were sectioned transversely and fractured longitudinally to determine the profile of the

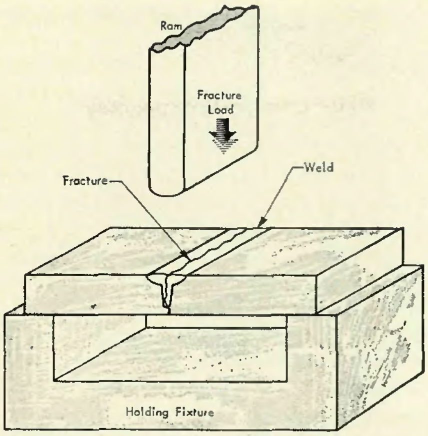



Fig. 2—Setup for longitudinally fracturing weld specimens

fusion zone and the penetration depth and variability.

## Results and Discussion

Initial attempts to obtain the experimental goal of 75-85% plate thickness penetration with a single, sharply focused electron beam welding pass invariably resulted in spike through, as indicated in Fig. 4. Experimentation revealed that a much more uniform penetration profile was obtainable by utilizing a defocused electron beam. Figure 5 graphically illustrates the manner in which penetration varies as a function of the electron beam diameters or power density. Typical penetration profiles of welds having 100 and 150 mil minimum penetration are seen in Figs. 6 and 7, respectively.

It is apparent that the problem of spike through can be avoided by utilizing a defocused welding beam. It should be realized, however, that this is accomplished at the expense of weld penetration.

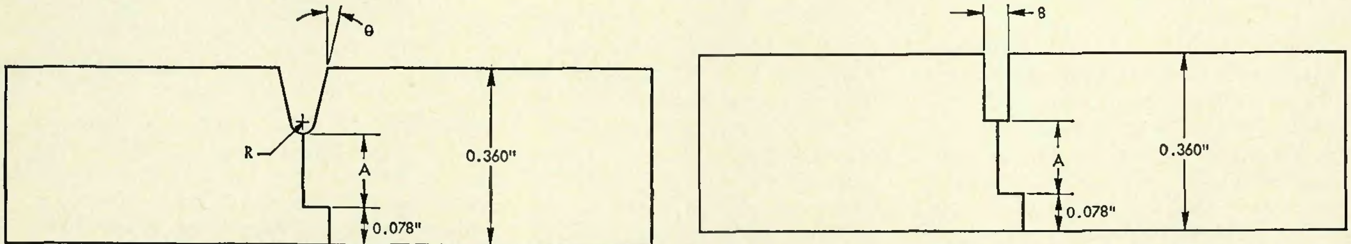
The original experimental goal of 75% (270 mils) minimum weld penetration in a 360 mil thick plate is not satisfied by 100 or 150 mil penetration. Several attempts to obtain the required partial penetration using a single defocused electron beam welding pass proved unsuccessful because of thermal damage at the root side of the weld and occasional spike through of the weld. A transverse section taken from a typical weld made with a single, defocused electron beam welding pass is shown in Fig. 8. The width of the heat-affected zone at the root of the weld indicates the severity of the thermal conditions at the back side of the joint. The heat-affected zone encompasses a nominal temperature range from 1,130 to 670° C—the melting temperature and alpha-beta allotropic transformation temperature, respectively.

To overcome the problems encountered with single-pass welds and to accomplish the original objectives, step joints and joints with backing strips were evaluated. A joint design comprised of a U-groove geometry (Fig. 3a) and multiple welding passes was derived to make welds that were free of any burn through. The root face, groove radius, and groove angle were varied to determine the optimum joint geometry.

In preliminary work, wire was fed into the joint after a root pass without filler metal was completed. This approach was discarded because wire feeding equipment suitable for remote operation in a vacuum environment was unavailable. Commercial wire feeders used in arc welding proved unsatisfactory for multipass electron beam welding.

Another method for filling the joint after an autogenous root pass was completed consisted of tacking a filler shim in the slot (Fig. 3b) and then melting the shim in place using a second welding pass to complete the weld. The method was abandoned because of inconsistencies in the fit up of the shim into the slot which tended to become distorted by the thermal effects of the root pass.

Subsequently, it was found that multipass autogenous welds could be made if joint dimensions were controlled to give a proper balance between the U-groove geometry, the root-face sizes, and the weld-metal buildup that results from solidification and shrinkage.




(a) U-Groove Joint Geometry Used for Making Wire Feed and Multipass Autogenous Welds

(b) Slot Joint Geometry Used for Making Consumable Insert (shim) Weld

Fig. 3—Joint geometries for the shim and wire feed and multipass autogenous electron beam welds. Dimension A varied from 50 to 150 mils; dimension B is dependent upon the selected shim dimensions. Dimension R varied from 10 to 30 mils; $\theta$ varied from 5-10 deg. Final dimensions for the multipass autogenous weld were: A—150 mils, R—20 mils, and $\theta$—7.5 deg.

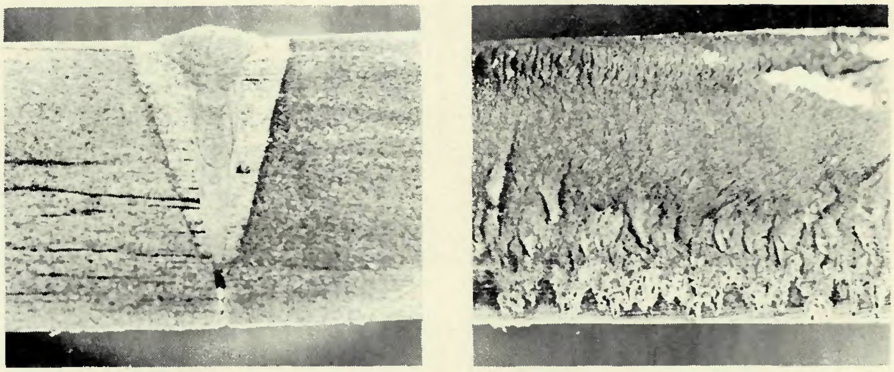


Fig. 4—Transverse-section profile (left) and longitudinal-penetration profile (right) for a sharply focused, partial-penetration electron beam weld in uranium—3/4 wt-% titanium alloy plate. Note degree of penetration variation and evidence of spike through at the root of the weld in the longitudinal view

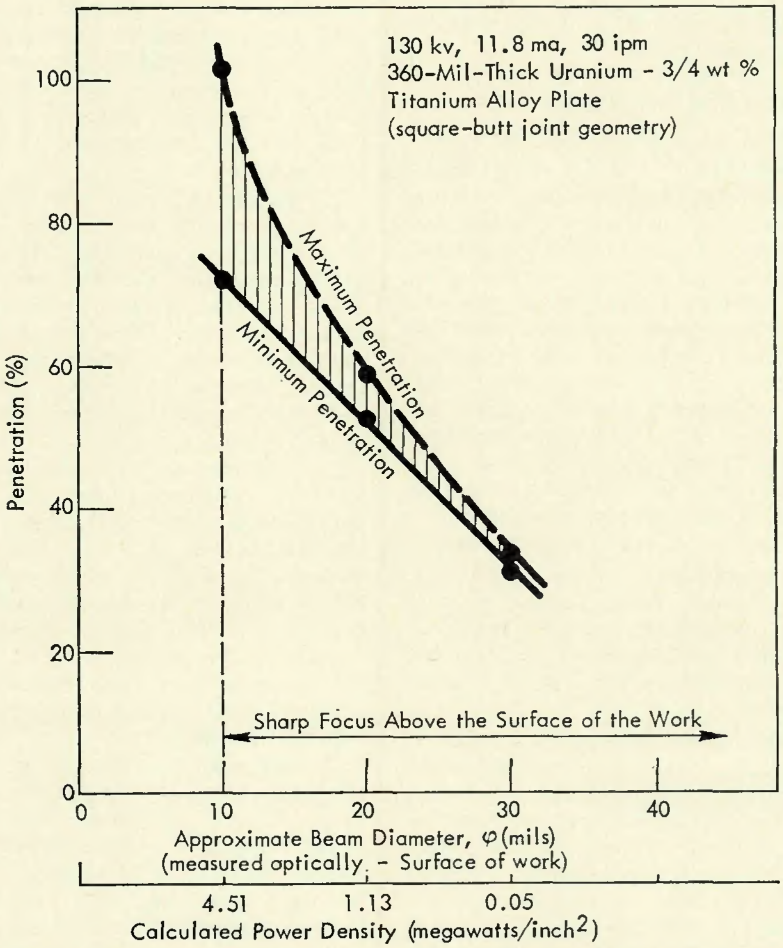



Fig. 5—Penetration variation as a function of the beam diameter (penetration variation or spiking is equivalent to the maximum minus minimum penetration at any particular beam diameter)

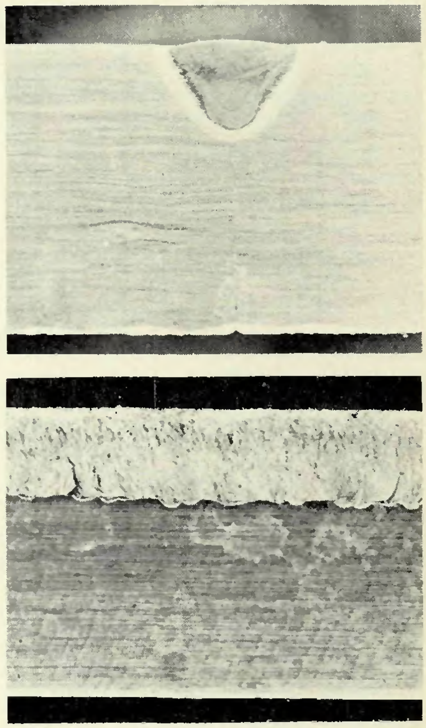


Fig. 6—Transverse-section profile (top) and longitudinal-penetration profile (bottom) of a 100 mil minimum-partial-penetration weld made utilizing a defocused beam. Welding parameters—130 kv, 7.5 ma, 30 ipm, defocused beam

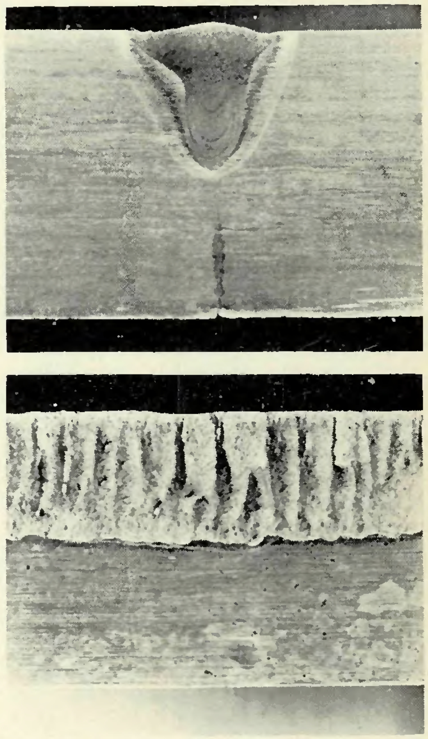


Fig. 7—Transverse-section profile (top) and longitudinal-penetration profile (bottom) of a 150 mil minimum-partial-penetration weld made utilizing a defocused beam. Welding parameters—130 kv, 11.7 ma, 30 ipm, defocused beam

Joint geometries for the multipass autogenous welds consisted of either a 100 or 150 mil root face, a 20 mil groove radius, and a 5 to 10 deg groove angle, depending on the root-face dimension. The best multipass welds were obtained using a joint with a 150 ± 2 mil root face, a 20 ± 2 mil groove radius, and a 8.5 ± 0.5 deg groove angle. The first welding pass fused the root face without melting the groove walls; the second pass made at 130 kv, 30 milliamp, and a travel speed of 30 ipm with the beam focused above the surface of the plate caused the groove to be filled without a filler metal addition. Nominal transverse weld shrinkage was 12 mils, and nearly all of this shrinkage occurred with the first welding pass.

A third welding pass made at approximately 8 kilojoules per linear inch of weld with the beam focused above the workpiece has also been utilized to gain additional groove filling. This additional groove filling is partially attributed to the mass transport associated with zone melting.[4] The third welding pass also served as a cosmetic pass having an extremely smooth surface that facilitated ultrasonic inspection of the completed weld.

Ultrasonic inspection was utilized primarily for determining the minimum weld penetration; however, by utilizing both a shear wave mode and a longitudinal mode, ultrasonic inspection for internal as well as root-weld flaws was possible.

Transverse section and penetration profiles of a completed two-pass, electron beam weld are illustrated in Figs. 9 and 10, respectively. A 20 mil thick embossment was added to the plate thickness, as shown in Fig. 9, to facilitate filling the groove. The embossment can be removed by postweld machining in cases where a smoother surface is desired. The main factors governing the filling of the U-groove were:

1. The decrease in groove width due to transverse weld shrinkage.
2. Mass transport caused by zone melting effects.
3. The amount of available base metal (in this case the embossment) which is suitably located such that it can be washed into the groove by the second and third welding passes.

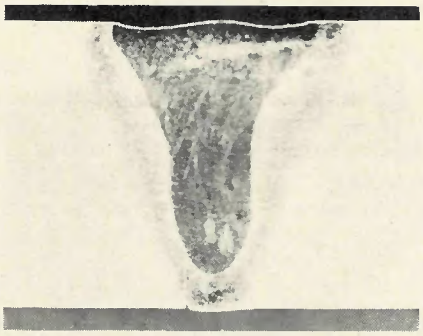


Fig. 8—Transverse section illustrating the weld profile of a single-pass, partial-penetration weld made utilizing a defocused beam

Another groove-filling method considered but not evaluated in this study is that of gravity filling by tilting the weldment such that gravity tends to transport molten metal toward the wake of the pool.

## Conclusions

Two principal conclusions have been reached as a result of this study:

1. Partial-penetration electron beam welds having a minimum penetration of 75% of the plate thickness in a 360 mil thick plate can be obtained utilizing multipass electron beam welding methods without experiencing melt-through or damage at the backside of the joint.
2. Partial-penetration electron beam welds having a minimum penetration of 75 to 85% of the plate thickness in a 360 mil thick plate cannot be obtained by utilizing single-pass electron beam welding methods without experiencing melt through and/or thermal damage at the backside of the joint.

### *References*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2. Hicken, G. K., and Booco, W. G., "Penetration Variations in Electron-Beam Welding", *Third International Conference on Electron and Ion Beam Science and Technology*, p. 398; John Wiley and Sons, Inc., New York, N.Y.
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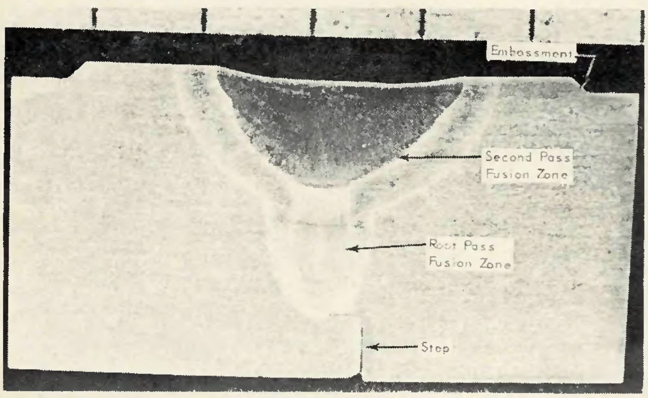


Fig. 9—Transverse-section profile of a completed two-pass, partial-penetration, electron beam weld. Note 20 mil thick embossment which was added to facilitate groove fill-up

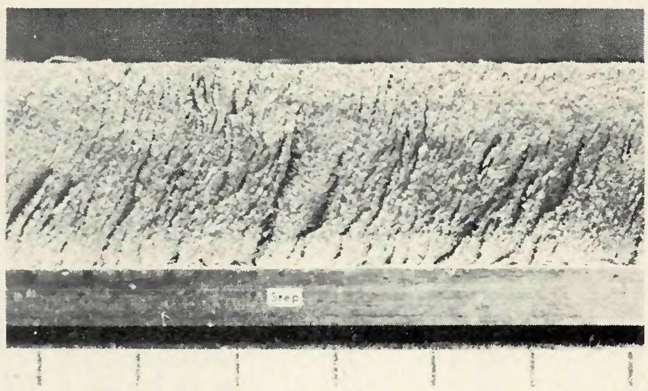


Fig. 10—Longitudinal (penetration) profile of the two-pass electron beam weld shown in Fig. 9. Unwelded interface at the root of the weld is the vertical segment of the step shown in Fig. 9.

*Announcing . . .* *April 28th . . .*

A symposium on the Fissuring of High Alloy Weldments will be sponsored by the Wrought High-Nickel Alloys Subcommittee of the Welding Research Council beginning at 9:30 A.M., Wednesday, April 28, in Room 104 at Civic Auditorium in San Francisco. The symposium is being held as part of the Technical Sessions Program at the 52nd Annual Meeting of the American Welding Society.

## Symposium Announcement . . . Thursday, April 29, 1971 . . .

The High Alloys Committee of the Welding Research Council will sponsor a symposium on the following topic on April 29:

**"Characteristics of Nickel-Base Alloy Weldments"**

The symposium is being held in conjunction with the 52nd Annual Meeting of the AMERICAN WELDING SOCIETY between 9:30 A.M. and 12:00 noon in Room 104 of Civic Auditorium, San Francisco, California. Included will be the presentation of the following short papers:

"Corrosion of Nickel-Base Alloy Weldments in Superheated Steam" by J. P. Hammond, P. Patriarca, and G. M. Slaughter, Oak Ridge National Laboratory, and W. A. Maxwell, Southern Nuclear Engineering, Inc.

"Acoustic Emission Characteristics of Postweld Heat-Treat Cracking in Rene 41 Weldments" by A. T. D'Annessa and J. S. Owens, Lockheed-Georgia Company

"A Mechanism for Cracking During Postwelding Heat Treatment of Nickel-Base Alloys" by M. Prager, Copper Development Association, and G. Sines, University of California at Los Angeles

"Methods for Improving the Weldability of High Strength Super-Alloys" by D. S. Duvall and W. A. Owczarski, Pratt and Whitney Aircraft

"Some Welding Problems with Inconel 718" by J. Gordine, Canadian Department of Energy, Mines and Resources

"Progress in the Welding of 50% Cr—50% Ni for Elevated Temperature Service" by E. P. Sadowski, International Nickel Co., Inc.

All are invited to attend and to participate in the audience discussion which is expected to ensue.