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Fusion zone during focused electron-beam welding

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Abstract

The effects of electron beam focusing characteristics on fusion zone are analytically investigated in this paper. The size and shape of fusion zone are important factors determining the weld quality during electron beam welding and depend on beam power, welding velocity, and focusing parameters. In this analysis, assuming the beam profile to be Gaussian distribution and considering the momentum balance at the cavity base and effective convection heat transfer, an analytical model for a focused electron beam irradiating into a paraboloid of revolution-shaped cavity on a workpiece is developed. The influences of the focal spot size, focal location relative to workpiece surface and beam-convergence angle on fusion zone are presented. Results reveal that a focused beam with small focal spot size and beam-convergence angle can induced a deep and narrow fusion zone and the deepest penetration occurs when the focal spot is located at the position between the workpiece surface and the bottom of fusion zone. The shapes of deep and shallow fusion zone approximate a cone with a spherical cap and a paraboloid revolution, respectively.

Keywords: Electron beam; Fusion zone; Focusing characteristics

1. Introduction

Electron beam welding is beneficial to many applications because of the high aspect ratios obtainable. An electron beam can be deflected and focused to a small cross-section, and thus an extremely high power density can be achieved. When the beam irradiates on a workpiece, the workpiece melts and vaporizes, resulting in a deep and narrow keyhole surrounded by fusion zone. As the beam is passed along the workpiece, the molten workpiece fills in the vaporized hole and solidifies. The main advantages from this technique are deep and narrow weld, defect free, minimal heat-affected zone and a high joining rate. Electron beam welding is a quite complicated process. It depends on a large number of parameters, concerning the thermal properties of materials and beam characteristics such as beam power, energy flux distribution, welding speed, focal location, focal spot size, and convergence angle. Precise knowledge is connected with the search, investigation and control of the welding process characteristics, which make possible the formation of sound welds with good reliability and mechanical properties. A deep, high quality weld require the appropriate values of beam power, beam profile, welding velocity, and focal location relative to workpiece surface. The importance for the beam focus location affecting the electron beam welding was found by Giedt and co-workers [1–3].

Adams [4,5] carried out comprehensive studies of the effects of beam focus location on joint penetration and fusion zone geometry for low- and high-voltage electron-beam welders. The depths and widths of the fusion zone for different top and bottom lens focus currents were measured. Illustrative results for an accelerating voltage of 130 kV and a beam current of 10 mA from a ribbon-type filament at a travel 60 in./min and a work distance of 6 in. showed that the maximum depth of the fusion zone was achieved with the beam focused about 1 in. below the workpiece surface. However, when focused at the surface, the decrease in depths of the fusion zone was only about 4%. At low power and low penetration, there is a tendency for the fusion zone to broaden with nonoptimum beam focus and for penetration to decrease relatively more than at high power and deep penetration. The sensitivity of the aspect ratio was found to increase with increasing distance from the focus coil to the work-

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piece. These trends are consistent with results presented by Engquist [6] who emphasized that a small error in the focus current can result in a significant change in the focal location and that it was best to operate at the shortest possible focus coil-to-workpiece distance. This study clearly established the importance of beam focus location.

Konkol et al. [7] measured the penetration and fusion zone by changing the focal distance with respect to work distance. The photographs of weld cross-sections showed that the deep and narrow fusion zone can be obtained when the focal location is slightly below the workpiece surface or the work distance decreases. On the other hand, the width of fusion zone increases but the depth decreases as the focal spot is away from workpiece surface. Some shapes of deep fusion zones approximate cones but some of shallow fusion zones are similar to paraboloid of revolutions. At a work distance of 6 in., the accelerating voltage, beam current, and travel speed were held constant at 150 kV, 100 mA, and 25 in./min, respectively. The focal distance for maximum penetration was found to be about 1.5 in. below the plate surface. These trends are consistent with the results presented by Adams [4,5].

The effect of beam focus was also investigated by focusing the beam at locations varying from 1 in. above to 1in. below the upper surface of the weld specimen surface [8]. Empirical relationships for the penetration versus beam energy distribution, beam power, beam moving speed and focal distance were also proposed. The average power per unit of penetration increases with the increasing beam speed and the penetration depth increases with the decreasing energy distribution parameter. Similar to the results measured by Konkol et al. [7], the fusion zone becomes wide and shallow when the distance between the focal location and workpiece surface increases. The shapes of fusion zone also have the same tendency between the results measured by Hicken et al. [8] and Konkol et al. [7] as the focal location relative to workpiece surface changes. For a work distance of 6 in., an accelerating voltage of 110 kV and beam current of 8 mA, when focusing the beam at locations varying from 1 in. above to 1 in. below the workpiece surface the penetration increases up to maximum and then decreases. The maximum penetration occurs for the beam focused about $0 \sim 0.5$ in. below the workpiece surface. Mladenov et al. [9] performed an experimental investigation of the weld depth and thermal efficiency during electron beam welding. The data revealed that when the ratio of work distance to focal distance approximates 1, the weld depth arrives at maximum.

Quantitative and theoretical confirmation for the effects of beam focusing characteristics on the penetration has been the subject of limited number of investigations. Wei and Chow [10] used a three-dimensional, quasi-steady heat conduction model [3] to interpret these effects. Their results revealed that for a small convergence angle, the incident electron beam produces a deep and narrow fusion zone, while a concave-shaped cavity for a large convergence angle. The parameters considered include the beam power, convergence angle, location of the focal spot, energy distribution at the focal spot, and beam speed. This model provides a quantitative understanding for the penetration of a focused electron beam but it is inconvenient to calculate the results due to the complicated numerical procedure. Therefore, the objective of this study is to derive a simple and practical model for predicting the penetration and fusion zone induced by a focused electron beam.

Swift-Hook and Gick [11] utilized the analytical and simple line-source model to calculate consistent shapes of electron-beam welds, provided the energy absorbed by the workpiece is known. However, the line-source model in its pristine form has certain defects. These are: (1) infinite temperatures occurred near the sources; (2) the distribution of incident flux was not taken into account. Wei and co-workers [12,13] found that the distribution of incident fluxes is an important factor affecting the depth of penetration; (3) vertical heat transport was neglected; (4) momentum balance was not taken into account. In order to avoid weaknesses of the line-source model, Wei and Shian [14] proposed a three-dimensional analytical model around the cavity produced by a moving distributed high-intensity beam, which considered the momentum balance at the cavity base and did not result in infinite temperature. On the basis of the model proposed by Wei and Shian, this work provided an analytical solution accounting for the effect of beam focusing parameters on the penetration. The main objective of this study was to systematically determine the variation of fusion zone with different focal locations, spot sizes, and convergence angles.

2. Analysis

2.1. Mathematical formulation

As sketched in Fig. 1, an electron beam continuously irradiates on the surface of the specimen with a constant speed so that a deep and narrow vapor-filled cavity surrounded by liquid and solid regions is produced. The fusion zone occurs as the liquid flow from the front to the rear [15–18]. This physical system can be considered to be a quasi-steady state process. Therefore, the mathematical model describing heat transfer in fusion zone can be written as:

$$-\hat{U}\frac{\partial \hat{T}}{\partial \hat{x}} = \alpha\left(\frac{\partial^2 \hat{T}}{\partial \hat{x}^2} + \frac{\partial^2 \hat{T}}{\partial \hat{y}^2}\right) + \alpha_z\left(\frac{\partial^2 \hat{T}}{\partial \hat{z}^2}\right) \quad (1)$$

The cavity can be a cone, paraboloid of revolution, or other irregular geometries during welding or drilling. For welding with a moving heat source the geometry becomes slightly asymmetric [3]. The cavity, however, can be roughly observed to be a paraboloid of revolution near the cavity base [19,20], especially for a deep and narrow cavity. Hence, the cavity is idealized by a paraboloid of revolution and a curvilinear orthogonal parabolic coordinate $\xi\eta\varphi$ system can be used effectively. Introducing the following transforms:

$$x = \frac{\hat{x}}{\hat{\sigma}} = \frac{2\sqrt{\xi\eta}\,\cos\varphi}{P_{\mathrm{e}}} \quad (2)$$