Measurement 129 (2018) 302–318

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Experimental investigations, input-output modeling, and optimization of spiking phenomenon in electron beam welding of ETP copper plates

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ARTICLE INFO

Keywords:
Electron beam welding
Spiking
Optimization
Genetic algorithm
Particle swarm optimization
Desirability function

ABSTRACT

The present study aims to determine the set of optimum process parameters in order to minimize spiking during bead-on-plate welding of ETP copper plates using electron beam. Accelerating voltage, beam current, welding speed, focus distance, amplitude and frequency of oscillations were considered as the input design variables. The spiking was characterized in terms of average penetration and standard deviation of penetration. Statistical regression analysis was conducted to correlate the spiking phenomena with the input parameters of electron beam welding. The reasons behind the spiking phenomenon and the associated porosity defects were also explained. This unconstrained optimization problem was solved using genetic algorithm, particle swarm optimization, and desirability function approach in order to maximize weld penetration and minimize standard deviation of penetration. The obtained optimized results were verified through real experiments and a good agreement between them was achieved. Genetic algorithm was found to perform slightly better than other approaches.

1. Introduction

Electrolytic tough pitch (ETP) copper has been widely used in the automotive, aerospace and nuclear sectors as an engineering material, due to its excellent properties, such as resistance to corrosion, good ductility, and high thermal and electrical conductivities [1–3]. Because of high melting point and thermal conductivity, the joining of thick copper sections (especially partial penetration welds) has been difficult by the existing welding techniques. Therefore, electron beam welding (EBW) has been chosen as an efficient joining technique for these thick copper sections [4].

EBW is an autogenous fusion welding process, in which intense heat energy required to fuse the metal is obtained by the impingement of the highly concentrated beam of accelerated electrons striking towards the material surfaces to be joined. This intense heat source has the capability of raising the temperature of the material to a high value in short period of time. Due to the thermionic emission, the electrons are generated inside a vacuum enclosure. A grid cup is utilized as a gate that controls the beam current and consequently, the electrons are shaped. A strong potential difference is applied between the emitter and anode, and consequently, the electrons are accelerated [5]. The arrangement of electromagnetic focusing lens setup concentrates the electron beam onto the work surface to an elongated spot to be welded.

With the aim of using electron beam for welding purposes, it should be focused at or near the workpiece surface. As the degree of focusing is increased, the beam current distribution deforms slowly because of the imperfect electron optics. The smaller and more concentrated beam results into deep penetration with the larger depth-to-width ratio. In partial penetration of welding, the defects, such as porosity, cold shuts, and spiking [6,7] occur in the weld bead. Moreover, in the case of partial welding, penetration depth is found to be not uniform in the welding direction, and this irregular penetration depth is a typical defect observed in the high energy density welding. This unexpected change in the local penetration in periodic successions increases the stress concentration on the localized tip and leads to crack at the keyhole root. The unsteady nature of the keyhole directs to the formation of gas bubbles that are frequently trapped within the weld metal when the fluid solidifies before the bubbles can escape [8,9]. This defect affects the mechanical and metallurgical properties of the welded component and leads to premature failure of the component. Several mechanisms of spiking formation have been reported in the literature.

Tong and Geidt [8] studied the formation of defects, such as spiking, rippling (humping) due to the oscillations of the keyhole during electron beam welding using X-ray. They had illustrated that spiking occurs

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https://doi.org/10.1016/j.measurement.2018.07.040
Received 20 April 2017; Accepted 15 July 2018
Available online 17 July 2018

when the closure fallback mechanism fails and a significant amount of the beam energy is concentrated on the keyhole root producing additional penetration. Thus, spiking phenomena depend upon the fluctuations of cavity oscillation and welding speed. Armstrong [10] investigated the effects of spiking in a deep partial-penetration EBW of depleted uranium material. They observed that in EBW, the decrease in power density of the beam in the cavity reduces spiking and obtains a smoother root, but simultaneously, it also decreases the depth of penetration. Finally, they concluded that spiking is a function of beam power density and total beam power, and it cannot be reduced without reducing penetration depth in EBW.

Johnson [11] studied various kinds of defects in bead-on-plate EBW on copper plates. He showed that the porosity had been increased with the increase in beam power, depth of focus and with the decrease of travel speed. It had also been showed that the material impurity had a clear effect on porosity, and an increase of the impurity level caused a decrease of beam penetration. Arata et al. [7] had investigated the macroscopic beam weld defects (except crack) and the occurring characteristics of R, A, AR-Porosity types, cold shut and spiking defects by using slope-welding. They concluded that the occurrence of R-porosity has no relation directly with penetration depth but it is closely related with spiking. It was also observed that the weld porosities were mostly influenced by beam current and beam active parameter (that is, the ratio of object distance to focal length). Phadke et al. [12] proposed a method of investigating spiking phenomena in electron beam welding by using a second-order continuous autoregressive model. A mechanistic model was developed for the spiking phenomena, which was then physically interpreted in terms of random fluctuation in the beam power. Finally, regression models were developed by correlating the spiking phenomena with the input parameters, namely accelerating voltage, beam current and welding speed. Tsukamoto and Irie [13] had explained the formation of spiking phenomena by correlating the behavior of the molten metal and the generation of X-rays from the beam-metal interaction points in EBW. According to them, the melting and spiking phenomena were clearly dominated by the molten metal's periodic flow in the cavity, which was caused by the natural vibrations of the molten metal flow or by high voltage power ripples. Shortly after the periodic ejection of molten metal, the beam cavity was vacant and then, the electron beam was free to impinge at the bottom, causing the spikes.

O'Brien et al. [14] had proposed two methods for suppressing the spiking phenomena in partial penetration EBW. The first method used a unique feedback system consisting of a side-viewing scintillation detection system coupled with the pulsing system, in which the beam current could be controlled by monitoring the X-radiation produced by the beam's interaction with the workpiece. The results indicated that the spiking phenomena could be suppressed on Al 7075 alloy. They used high duty cycle frequencies lying in the range of 100 Hz–1000 Hz, that is, pulsed EBW to suppress the spiking phenomena in the second method. They found that spiking phenomena could not be suppressed by the above pulsing parameters. Mara et al. [15] compared both full and partial penetrations in EBW on the basis of beam-metal interactions with an x-ray pinhole movie camera and examined the effects of beam power density. Their results showed that the spiking could be suppressed with an appropriate pulsing schedule, which would maintain the oscillatory nature of the point of beam impingement. Schauer et al. [16] proposed a concept based on the measured temperature distributions and length ratio in an EB weld cavity, where it was concluded that the vapor pressure and surface tension could dominate the lower and upper regions, respectively. The region where these two forces become approximately equal is unstable, and the surface tension force could cause in word flow of liquid metal, which tends to form a projection causing spiking. For a specific material, the location of projection was found to be dependent on the depth of the cavity. Arata et al. [17,18] analyzed the formation behavior of the internal defects, such as spiking, cold-shuts, and R-porosity in the case of both conventional welding as well as Tandem EBW methods. They had also compared single EBW with beam oscillations and Tandem EBW with the help of a high-speed imaging technique. Tandem EBW showed much more effectiveness when compared to the conventional EBW with oscillations. Kautz et al. [19] used pulsed electron beam for the welding of type 21-6-9 stainless steel. From their observations, they concluded that an increase of heat input might cause a small increase in penetration but it had a significant contribution towards root irregularities. Further, they clearly indicated that the pulsed electron beam welding in a keyhole mode was not suitable for most of the applications. Wei et al. [20] investigated experimentally the mechanisms of fusion-zone defects, such as spiking and humping during the keyhole mode of electron-beam welding on Al alloys and SS 304 plates. Their results showed that the amplitudes of humping and spiking increased with the low welding speed and high volatile element Mg in Al 5083. They concluded that the frequency and amplitude of spiking, however, could be increased by lowering the focal-spot location. Cho et al. [21] carried out single-mode fiber laser welding on the SS304L material. They showed that laser welds with the large focal lengths appeared to have spiking defects and also the magnitude of spikes was larger for the deeper welds. Trushnikov et al. [22] studied the influence of the longitudinal and transverse deflection oscillations on EB welds. They concluded that the use of beam deflection oscillations does not change the bottom part of the keyhole. Liu and He [23] proposed a 3D mathematical model to investigate the physical transport phenomena of weld-pool and vapor plume throughout the partially-penetrated electron beam welding on 2219 aluminum alloy plate. From their analysis, they concluded that with the increase of beam current, there is an increase in the evaporation intensity, keyhole wall temperature, keyhole depth, and instability, which produce a spiking defect in the weld.

Badkar et al. [24] used response surface methodology (RSM) and central composite design for modeling and optimization of laser welding. Modeling was carried out using nonlinear regression to establish relationships between the inputs and responses of laser welding. They used desirability function approach also to optimize the laser power, scanning speed and focused position to get suitable weld bead width and bead depth. Dey et al. [25] conducted bead-on-plate (BOP) welding of SS304 plates utilizing EB welding machine. Experiments were conducted following the central composite design, and statistical regression was carried out to establish an input-output relationship of the EB welding. An optimization problem was mathematically formulated to minimize the weldment area after maintaining the maximum bead penetration. This process was optimized utilizing a genetic algorithm (GA) along with the penalty function approach. The optimal results, thus obtained, were verified through real experiments and a close match between them was found. Anand and Elangovan [26] had proposed RSM-GA integration technique to maximize the pull-out strength of the joint produced by ultrasonic insertion process. Inserting time, holding time and pressure were considered as input parameters for the process. Experiments were conducted according to the central composite design (CCD). Nonlinear regression was carried out to model input-output relationships of the process.

Munish et al. [27] had explained the application of RSM and particle swarm optimization (PSO) technique for optimization of three input machining parameters in turning of Titanium (Grade-II) alloy under minimum quantity lubrication (MQL) environment. They used multiple regression techniques for the modeling of responses, desirability approach and PSO for optimization of input parameters. Katherasan et al. [28] used Taguchi L25 to design the experiments for the input variables (wire feed rate, voltage, welding speed and torch angle) in flux-cored arc welding of 316L (N) austenitic stainless steel. The artificial neural network was used to establish the relationship between the inputs and responses (bead width, reinforcement and weld penetration) of the bead-on-plate welding process. An optimization problem was formulated to maximize the weld penetration subjected to the minimization of bead width and reinforcement. The optimization