Abstract

Electron beam (EB) welding is one of the state-of-the-art welding processes with inherent advantages of high aspect ratio, low heat input, and minor defects. One of the high energy density welding processes, EB welding, is preferred for welding nuclear, aerospace, and automotive materials. Electrolytic tough pitch (ETP) copper component and precipitated hardened (PH) CuCrZr alloys are used as diagnostic neutral beam and heat-sink materials, respectively, in International Thermonuclear Experimental Reactor (ITER) for heat extraction from plasma-facing components. The feasibility and reliability of autogenous EB welded ETP Cu and CuCrZr alloy are primary research interests within the ITER context. Electron beam butt welding of CuCrZr alloy plates was carried out to correlate the effects of heat input, beam current, and welding speed on microstructural and mechanical properties of the joint. Microstructural and precipitation behaviours of different zones of the joint were analyzed using X-ray Diffraction (XRD), Energy Dispersive X-ray Spectrometry (EDS), and transmission electron microscopy (TEM). Additionally, Machine learning-based tools, like support vector regression (SVR) for prediction and unsupervised clustering algorithm for classification, were used to access the quality of the CuCrZr welded joint from bead surface attributes without offline destructive testing. Furthermore, 3D visualization and quantification of porosity in EB welded copper plate were investigated. An attempt had been made to study the formation of spiking and spatter in the joint with the beam's varying beam power and oscillation amplitude. The welded copper plates were examined using micro–X-ray Computed Tomography (XCT) for porosity characterization and their quantification. An adaptive neuro-fuzzy inference system (ANFIS) based modeling had been attempted to predict the severity of spiking defect of the copper joints. In addition, a swarm intelligence-based multi-objective approach was used to minimize spiking and maximize the weld penetration to handle the conflicting objectives.

An increase in welding speed ensures enhancement of solidification rate, finer grains, keyhole profile and minimization of heat-affected zone, Cr-depletion and residual tensile strain. On the contrary, an increase in beam current has an inverse relation with thermal gradient, solidification rate, grain size, ductility and micro-hardness but yields increment in Cr-depletion, residual tensile strain, weld bead and HAZ width. The coarse grain, presence of residual stress, decrease in precipitate concentration, and concentration of intermetallic like Cu_5Zr and Cu_5Zr_{14} were observed in the fusion zone (FZ), and it might be the possible reason behind the degradation of tensile strength and microhardness. Beam power was found to have more influence than the amplitude of beam oscillation on porosity formation and spatter in the copper welded joint. The probability of obtaining the spatter and porosity increased with beam power. Hydrogen and oxygen were found to be the prime residual gases causing gas porosity in the weld. A low level of frequency and a high level of amplitude oscillation were found to be suitable for minimizing spiking in the welds. Moreover, a low accelerating voltage and beam current with the high scan speed, and beam focused away from the surface were the primary requirements to control spiking phenomena. As classified by clustering algorithms, the high voltage and current with moderate welding speed were the recommended parameters to get a high strength CuCrZr joint. Keyhole-based weld profile could be acquired by utilizing high beam power and welding speed.

Keywords:

Electron beam welding; Copper alloy; CuCrZr; Mechanical properties; Metallurgical study; XCT; Porosity; Spiking; ANFIS; Multi-Objective Optimization; Bonobo optimizer; Particle swarm optimization; Clustering; Support Vector Regression; Machine Learning