Abstract:

In industrial environment, the operating conditions pose challenges to the performing material, especially its welded joints, due to prevalence of high temperatures, pressure as well as aggressive environment. In a fabricated structure, weldment region is often considered as the weakest section where failure initiation occurs due to the presence of welding defects. Compared to cost effective conventional arc welding techniques, methods based on high energy density heat sources with minimum heat input like electron beam welding (EBW) or laser beam welding has an edge towards minimizing the heat damage to the material. EBW is one of the advanced and emerging welding processes with additional advantages like producing cleanest possible joint under vacuum environment, thicker weld in single pass, producing tougher joint for difficult to join dissimilar materials etc. Beam oscillation is an important process variable in EBW, which is reported to produce a churning action in the liquid weld pool reducing defects. However, effect of beam oscillation on similar and dissimilar welds has not been explored for several metal/alloy systems.

In the present study, three different weld configurations such as copper to 304SS, 316L SS to 316L SS and Ti-6Al-4V to Ti-6Al-4V were butt welded using EBW with oscillating beam of two different diameters (1 and 2 mm) as well as non-oscillating beam. The joints were thoroughly inspected for their soundness using X-ray radiography as well as three dimensional X-ray computed tomography. Subsequently, they were characterized comprehensively by microscopic investigations, residual stress measurements and aqueous corrosion tests. The mechanical properties were evaluated by performing various tests like microhardness, tensile, Charpy impact, three point bend, creep and low cycle fatigue etc. in accordance with the ASTM standards.

In copper–304SS joints, it was observed that joints prepared using oscillating beam with optimum oscillation diameter produced excellent mixing in the weld pool leading to evolution of more homogeneous microstructure and enhanced properties especially ductility and impact strength. Such joints also demonstrated presence of fewer defects like porosity and microcracks. Moreover, majority of the cracks were found to be back filled by copper owing to better mixing. In case of joints produced

with oscillating beam of higher oscillation diameter, large amount of copper was found in the fusion zone in the form of chunks. Such observations may be attributed to melting of more copper, limited dissolution of copper in iron, and localized copper segregation. Such non-homogeneous microstructure possibly is the cause of stress generation, formation of microcracks and porosities in the segregated copper in the fusion zone. Use of non-oscillating beam did not facilitate either melting of enough copper or its mixing to produce a tough joint. However, the results pertaining to aqueous and pitting corrosion tests demonstrated that joints prepared with oscillating beam had poor corrosion resistance. This may be attributed to prevalence of less amount of copper in intimate contact with steel in the fusion zone forming galvanic couple.

All the 316L SS joints irrespective of their employed welding conditions were found to be perfectly sound and defect free. Joints prepared with oscillating beam demonstrated narrow fusion zone with fine grained microstructure of lathy ferrite morphology. While joints produced with non-oscillating beam showed evolution of ferrite in skeletal morphology. Moreover, joints prepared with oscillating beam demonstrated the presence of higher content of delta ferrite in the fusion zone, lower residual stress, better pitting and aqueous corrosion resistance, better mechanical properties like higher notch tensile and Charpy impact strength as well as higher creep rupture life. It is worth mentioning that unlike Copper–SS joints, 316L SS similar joints prepared with higher oscillation diameter demonstrated better properties which may be attributed to better mixing in the absence of any liquid separation.

Ti-6Al-4V similar joints produced with oscillating beam of 2 mm diameter were found to exhibit better properties as those of 316L SS joints. They not only possessed narrowest fusion and heat affected zones but also minimum defects like porosity, undercut etc. Their fusion zone microstructure demonstrated the presence of acicular α' martensite with reduced content of retained β phase. Accordingly, even if they possessed slightly higher residual stress values but such stress values were considerably lower than joints prepared by arc welding. They also demonstrated better pitting corrosion resistance and bio-compatibility, improved Charpy impact strength, fatigue life, and higher % elongation than those produced with non-oscillating beam.

However, joints prepared with higher oscillation diameter registered better mechanical properties than those made with lower diameter.

Finally, a hypothesis has been proposed to throw more light on the prevalence of better heat and mass mixing in the weld pool during the use of an oscillating beam.

Keywords: Electron beam welding (EBW); Beam oscillation, Copper; Stainless steel (SS); Ti-6Al-4V; Microstructure; Mechanical property; Corrosion; Residual stress; Defect analysis