ABSTRACT

Welding of titanium and its alloys and niobium are of major concern because of their high chemical reactivity and the requirement of defect-free and precision/narrow weld zone with a minimum heat-affected zone. Though conventional techniques like tungsten inert gas (TIG) and metal inert gas (MIG) are used for welding, however, the presence of inclusions in the weld zone, different defects and the formation of wide weld zone and heat affected zone are the problems associated with conventional welding of titanium and its alloys & niobium. Electron beam welding (EBW) is an advanced welding technique which produces a defect-free joint with a narrow and precision weld zone and a negligible heat-affected zone. In the past, though EBW has been successfully applied for the welding of titanium, its alloys and niobium, however, the effect of beam oscillation as a process parameter on the characteristics and properties of the weld zone has yet to be studied in detail in case of titanium and niobium. The present thesis concerns a detailed investigation of the effect of process parameters (e.g., beam current, welding speed, and beam oscillation) on the microstructures, mechanical and electrochemical properties of weld zone developed in similar joints of titanium and its alloys (CP Ti and Ti6Al4V), and pure niobium developed by electron beam welding. The objectives of the thesis have been divided into three parts: (1) Detailed study of the electron beam welding of similar CP titanium joints, (2) Detailed study of electron beam welding of similar Ti6Al4V alloy joints, and (3) Detailed study of electron beam welding of pure niobium similar joints.

Electron beam welding of CP Ti and Ti6Al4V was carried out using an in-house 80 kV, 12 kW EBW machine installed at IIT Kharagpur. A similar joining of CP Ti has been carried out using a constant acceleration voltage of 60 kV, beam current of 40 mA, welding speed of 900 mm/min, and varying circular beam oscillation of 0 to 1.5 mm. The similar joining of Ti6Al4V has been carried at a constant voltage of 60 kV with varying scan speeds (800 mm/min to 1000 mm/min) and beam current (42 mA to 48 mA) using the oscillated (1-2 mm) and un-oscillated beams. A 60 kV, 15 kW electron beam welding (EBW) machine located at the Inter-University Accelerator Centre (IUAC), New Delhi, has been used for the similar joining of pure niobium. The welding of niobium has been carried out using an acceleration voltage of 50 kV, welding speed of 150 mm/min, and beam current of 62 mA using an oscillated and un-oscillated beam.

The detailed study involves understanding the effect of process parameters on surface morphology, bead geometry, microstructure, residual stress, microhardness, wear resistance, and electrochemical properties.

The EB welding of similar CP Ti resulted in the formation of full-depth penetration joints with no visual defect. The average surface roughness of the EB welded CP Ti samples increased (3.1 µm to 3.59 µm) in the bead regions compared to the base metal (5.2 µm). Also, the average surface roughness (Ra) increased with an increase in beam oscillation diameter. The microstructure of the fusion zone showed the formation of a mixture of α and α' titanium phase compared to only α phase in the base metal. The phase analysis shows the presence of only the α'-titanium phase in the fusion zone. There is an introduction of tensile residual stress in the fusion zone of all the joints, with the magnitude varying from (420 MPa–480 MPa) compared to 6 MPa of base metal. Residual stress was 420 MPa with un-oscillated, and it increased (432 MPa – 480 MPa) due to the application of an oscillated beam. The microhardness was also increased in the fusion zone (250 VHN – 265 VHN) and HAZ (243 VHN -245 VHN). The introduction of an oscillated beam reduced the microhardness in the fusion zone. The sample welded without beam oscillation showed the highest microhardness (265 VHN) and decreased with the increased beam oscillation diameter. Due to electron beam welding without beam oscillation, there is a marginal reduction in yield strength (465 MPa to 462 MPa), ultimate tensile strength (626 MPa to 623 MPa), and % elongation (18.2.% to 14%) as compared to as-received titanium. The introduction of beam oscillation and increase in oscillation diameter leads to a further reduction in yield strength (457 MPa to 452 MPa) and ultimate tensile strength (623 MPa - 622 MPa) as compared to static beam (YS: 462 MPa, UTS: 6263 MPa). whereas the percentage elongation increases (15% - 18%) with an increase in oscillation diameter as compared to the static beam (18.2%). The fractography of the failed surfaces showed a mixed-mode fracture. Nano-hardness of the EB welded CP Ti increases after welding. The application of beam oscillation reduced the nano-hardness of the fusion zone, which was reduced further with the increase in beam oscillation diameter. Young’s modulus of the weld zone was higher when the static beam was applied. However, it reduced when the oscillated beam was applied and reduced further with increased beam oscillation diameter. The energy absorbed during elastic regimes increases with beam oscillation diameter. The potentiodynamic polarization test in 3.5 wt.% NaCl solution shows that the corrosion resistance of EB welded CP titanium increased compared to the as-received one. The corrosion resistance of the sample welded with the oscillated beam was greater than the static beam, increasing with the beam oscillation diameter. The fretting wear resistance of the EB welded CP Ti against a WC ball increased with the beam oscillation diameter.

Electron beam welding of Ti6Al4V led to the formation of defect-free welding with the presence of α, α' martensite, and a few β phases in the microstructure. The width of the fusion zone was found to vary from (4.8-5.5 mm), and the width of the heat-affected zone was found to vary from (0.38 – 0.6 mm). A detailed study of the texture variation by EBSD showed that texture and the area fraction of low/high angle grain boundaries vary with process parameters, but no specific trend on the variation with process parameters was observed. The average Kernal misorientation angle of the electron beam welded samples varies from 0.49° - 0.57° compared to 0.40° for as-received Ti6Al4V. The hardness of the fusion zone of EB welded joints increased due to the formation of α' martensite phase compared to as-received Ti6Al4V. Residual stress generated in all the joints is tensile in nature (520-620 MPa), and it reduces as we move from the fusion zone to the heat-affected zone and base metal (350 MPa). The yield strength, ultimate tensile strength and % elongation of the joints was marginally reduced (YS: 878-934 MPa, UTS 878-934 MPa, % elongation: 7.3 -11.3 %) compared to the as-received Ti6Al4V (YS: 934 MPa, UTS: 935 MPa, 17.3 %). Potentiodynamic polarization study in a 3.5 wt.% NaCl solution shows better corrosion resistance for the samples welded with beam oscillation than the case where beam oscillation was not used. Electrochemical Impedance Spectroscopy measurement reveals the formation of a complex passivating film in the case of EB welded joints. Finally, the X-ray photoelectron spectroscopy (XPS) analysis of the post-corroded samples shows the presence of titanium oxide (rutile and anatase) on the surface in the case of electron beam welded samples compared to only anatase in as-received corroded Ti6Al4V. The wear kinetics against a 10 mm WC ball fretting wear mode is marginally reduced (0.000109-0.000106 mm^3/mm) compared to 0.00015 mm^3/mm of the base metal. The wear mechanism was identical for the weld zone and the as-received Ti6Al4V. The wear mechanism was predominantly fretting-assisted abrasive wear in both cases.

Electron beam welding of pure niobium processed using optimum current, voltage, and scan speed results in full-depth penetration weld with visually defect-free seam. The average surface roughness (Ra) of the welded region increased after EBW. Also, the average surface roughness in the bead region was higher for the sample welded with the oscillated beam (3.6 µm) than the un-oscillated beam (2.37 µm). In the electron beam welded niobium, there is a coarsening of microstructure in the weld zone. Grain size in the range of 1 mm has been in the fusion zone as compared to 20 µm in the as-received material. It is observed that there is an increased area fraction (82% to 94%) of low-angle grain boundary (<15°) in the weld zone as compared to the base metal (75.2 %). Beam oscillation does not influence the microhardness. The nano-hardness of the welded niobium increases after EBW. The nano-hardness of the samples welded with the oscillated beam is higher than that of the case where no beam oscillation was used. No new phase has formed after electron beam welding, but a strong texturing effect along the (110) plane has been observed in the fusion zone. Beam oscillation also increased the residual stress in the fusion zone (358.1 MPa) compared to the static beam (223.3 MPa). The magnetic moment per gram of the EB welded niobium decreased due to the application of beam oscillation. The magnetic moment per gram is found to be 0.35 emu for the oscillation beam compared to 0.38 emu for the un-oscillated beam and 0.40 emu for as-received niobium. In addition, beam oscillation caused increased resistivity in the weld zone due to the introduction of a larger volume fraction of micro porosities (0.4 vol%) as compared to the static beam (0.3 vol. %).

Keywords: Electron Beam welding, CP titanium, Ti6Al4V, Niobium, Wear, Corrosion.