PREFACE

Titanium alloys are increasingly being used in the aerospace and nuclear industries due to their high strength-to-weight ratio, superior mechanical properties, and excellent corrosion resistance. However, welding these alloys using conventional processes remains challenging due to their high affinity for atmospheric gases at elevated temperatures (above 480 °C) and the severe grain coarsening in the heat affected zone (HAZ) and weld region. Welding dissimilar titanium alloys becomes even more challenging due to the varying compositions and properties of different titanium alloys. These differences can lead to variations in melting temperatures, thermal expansion rates, thermal conductivity, and metallurgical compatibility during welding. Therefore, welding of dissimilar titanium alloys requires careful consideration of material properties, welding techniques, and process parameters to achieve high-quality and reliable welds. The demand for dissimilar welding of titanium alloys is increasing in modern industries due to the requirement for innovative, high-performance, and cost-effective products and structures that take advantage of the strengths and other properties of different materials while addressing specific design and functional requirements. Among all welding processes available for welding titanium alloys, gas tungsten arc welding (GTAW) and its variants are the most affordable welding processes and have the capability to produce welds with good mechanical properties.

The present investigation focuses on developing defect-free autogenous dissimilar butt welds between commercially pure titanium (α-alloy) and Ti-6Al-4V ((α+β)-alloy) using pulsed-gas tungsten arc welding (pulsed-GTAW) and characterizing the produced welds in terms of microstructural evolution, phase development, and mechanical properties. For the development of atmospheric contamination-free welds, a novel shielding setup has been designed, developed and assembled with the pulsed-GTAW machine. The shielding setup effectively protected the weldment from atmospheric contamination without the need for additional shielding such as box shielding or trailing cups. In other words, the ceramic nozzle of the GTAW torch (primary shielding) provided during welding was sufficient to protect the weldment from atmospheric contamination. The welds prepared using the developed shielding set-up at optimised gas pre-flow and post-flow times had a silvery-bright colour on the top and root sides of the welds and were free from any kind or cracking or atmospheric contamination. Unlike conventional-GTAW (without current pulsing), the pulsed-GTAW process prevented grain growth in the HAZ and weld regions of the weldment.

The GTAW process is a low arc density process that generally produces a wide and shallow weld pool, coarse grains in the HAZ and weld regions, and large distortions in the weldment. Therefore, each welding process parameter must be optimized to mitigate these shortcomings. Initially, to observe the effect of current pulsing, the bead on plate welding was performed on 2 mm thick Ti-6Al-4V sheets. The current pulsing during welding helped in achieving the average prior-β grain size in HAZ of 37 μm and 105 μm in the weld region, which is significantly lower than the average prior-β grain size obtained using conventional-GTAW (60 μm and 165 μm in the HAZ and weld, respectively). The current pulsing during welding also helped in improving the hardness in the HAZ and weld regions over those obtained with conventional GTAW.

Electrode tip angle is an important process parameter that affects the geometrical elements of the weld and distortions in the weldment. The effect of electrode tip angle was investigated by performing bead on plate welding on 2 mm thick commercially pure titanium (CP-Ti) sheets using electrode tip angles of 30°, 45°, 60°, 75°, and 90° through pulsed-GTAW. The weld's geometric elements were measured and analyzed using a stereomicroscope and Image J software. The findings revealed that as the electrode tip angle increased from 30° to 90°, the weld bead width decreased continuously from 6.84 mm to 5.32 mm. Additionally, weld penetration initially increased from 1.59 mm to 1.75 mm up to a 60° tip angle but then gradually decreased to 1.51 mm at 90°. Furthermore, increasing the electrode tip angle led to a reduction in weld distortion. The current pulsing during GTAW not only assisted in grain refinement in the weld due to intermittent melting and solidification, but also improved weld penetration and reduced the width of both the HAZ and the weld region.

To observe the individual effects of pulse parameters such as peak current (I_p), background current (I_b), peak current time (t_p), and background current time (t_b), bead on plate welding was performed on a 2 mm thick CP-Ti sheet at a constant frequency of 5 Hz and mean current of 100 A. The current levels for the experiments were selected in such a way that the effect of pulse parameters on weld penetration and weld bead width could be visually observed. Two-step I_b and three-step t_b were varied in steps of 10%. The effect of changes in I_b% and changes in t_b% on weld bead geometry were studied and analyzed using stereomicroscope and ‘Image J’ software. The effects of changes in t_b on weld penetration and reduction in weld bead width were more pronounced compared to the changes in I_b. The maximum weld penetration and minimum weld bead width were observed with 40% of I_p as background current and 70% of the total cycle time as the time for background current. Further reductions in background current resulted in large undercuts or burn-throughs in the plates being welded.

The optimized pulse parameters derived from the above study were used for dissimilar autogenous butt welding of 2 mm thick CP-Ti with Ti-6Al-4V sheets at a frequency range of 3 to 5 Hz with intervals of 0.5 Hz. The results obtained were compared with dissimilar welds produced using the conventional GTAW process. Visual inspection, X-ray radiographic analysis, metallographic studies, energy dispersive X-ray spectroscopy (EDS) analysis, X-ray diffraction (XRD) analysis, microhardness measurements, tensile testing, Charpy impact testing, and fractography of tensile and impact test specimens of dissimilar welds were carried out to understand the evolution of the microstructure and to characterize the welds for their mechanical properties. Zone-wise impression creep analysis of the dissimilar weld was also carried out to predict the behaviour of the welds in high-temperature environments.

All the welds produced met X-ray radiographic quality standards and were free from any subsurface defects. An increase in pulsed frequency contributed to the refinement of the microstructure in the weld and the heat-affected zone (HAZ) region. The Widmanstätten basket-weave morphology was observed in the microstructure of dissimilar welds. The refinement in morphology was observed with an increase in pulse frequency during welding. XRD analysis was performed to observe the appearance of phases in the weld region. XRD analysis of dissimilar welds confirmed the presence of only α and β phases, and no peaks corresponding to any unwanted phases like titanium oxides were observed. To assess the variation of elemental composition throughout the weld, EDS analysis was performed. The EDS results confirmed that non-uniform mixing throughout the weld region. The lightweight aluminium exhibited superior mobility and was almost uniformly distributed throughout the weld. However, vanadium, which is heavier, appeared relatively less mobile, and more variation in the weight percentage of vanadium was observed throughout the weld. Dissimilar welds produced using pulsed-GTAW showed relatively better mixing, and solute particles were more uniformly distributed when compared to welds produced using conventional-GTAW. This improvement in mixing using the pulsed-GTAW process was attributed to the increased agitation generated by current pulsing and the higher temperature achieved due to the to the high peak current.

An unsymmetrical variation in hardness was observed in the weld region due to the to the non-uniform mixing of solute elements. The average hardness in the weld center was 286 $HV_{0.2}$ for the weld prepared using pulsed-GTAW at a frequency of 5 Hz, while the average hardness was 281 $HV_{0.2}$ at the weld center of conventional-GTAW weld. The maximum average hardness (~342 $HV_{0.2}$) in the weldment was observed in the base metal of Ti-6Al-4V, and the average hardness in the base metal of CP-Ti was around 135 $HV_{0.2}$. The strength of the weldment was assessed by preparing two types of tensile specimens from the dissimilar welds. Non-standard reduced-section tensile specimens were prepared to assess the strength of the weld region of dissimilar weld by intentionally reducing the cross-section in that area and compared with the base materials. Additionally, full-length standard tensile test specimens were prepared to determine both the weakest region and the maximum

strength of the weldment. The results of the reduced-section tensile specimens revealed that a maximum yield strength of 380 MPa and ultimate tensile strength (UTS) of 570 MPa were obtained for welds prepared using pulse-GTAW at a frequency of 5 Hz. In contrast, the minimum yield strength of 265 MPa and UTS of 453 MPa were observed for welds prepared using conventional GTAW. The full-length standard tensile specimens fractured in the HAZ of the CP-Ti, indicating it as the weakest region of the weldment. An improvement in UTS to 376 MPa and a reduction in elongation to 13.3% at fracture were observed for the welds produced using pulsed-GTAW at 5 Hz frequency, compared to the welds produced using conventional-GTAW, where a UTS of 323 MPa and elongation of 24.3% at fracture were obtained.

Charpy impact tests were performed to determine the impact energy of various regions within the weldments, including the weld region, the heat-affected zone (HAZ) on the CP-Ti side, the HAZ on the Ti-6Al-4V side, and the base metals. These tests were conducted on weldments prepared using conventional GTAW and pulsed-GTAW at a 5 Hz frequency. A decrease in impact energy was observed in both the HAZ and weld regions of the pulsed-GTAW weldment compared to the conventional-GTAW weldment. This decrease was attributed to the formation of hard and brittle phases in the pulsed-GTAW weldment. Specifically, the impact energy of the HAZ in CP-Ti decreased by 50% from the base CP-Ti impact energy of 200.9 J/cm^2 due to grain coarsening. On the other hand, although the base Ti-6Al-4V had a low impact energy of 17.7 J/cm^2, the impact energy of its HAZ increased significantly to approximately 100 J/cm^2. This improvement was attributed to the appearance of Widmanstätten morphology in the HAZ of Ti-6Al-4V.

To assess the creep behavior of different regions within the dissimilar weldment, impression creep testing was performed on all five regions: base CP-Ti, HAZ of CP-Ti side, dissimilar weld, HAZ of Ti-6Al-4V, and base Ti-6Al-4V. The presence of coarse prior-β grains and Widmanstätten morphology in the HAZ of Ti-6Al-4V, as well as in the weld region, contributed to reducing grain boundary sliding and impeding dislocation glide, respectively. This resulted in improved creep resistance in these areas. Notably, the HAZ of Ti-6Al-4V exhibited the highest creep resistance among all regions of the weldment. In the testing range of temperatures and stresses, dislocation creep appeared as the governing creep mechanism, with activation energies ranging from 134.56 kJ/mol to 302 kJ/mol across different regions of the weldment.