Chapter 5 : Summary and Conclusions

The present investigation focused on developing defect-free autogenous dissimilar butt welds of 2 mm thick commercially pure titanium (CP-Ti) and Ti-6Al-4V alloy sheets, using pulsed-GTAW (p-GTAW) at a pulse frequency range of 3-5 Hz, with 0.5 Hz intervals. The study analyzes the microstructural evolution and mechanical properties of these dissimilar welds. Atmospheric contamination-free welds were produced using an indigenously developed shielding setup integrated with the p-GTAW machine. This setup effectively protected the weldment from atmospheric contamination without the need for additional shielding, such as box shielding or trailing cups. All the welds met X-ray radiographic quality standards and were free from subsurface defects.

An increase in pulse frequency contributed to microstructural refinement in both the weld and the heat-affected zone (HAZ). The Widmanstätten basket-weave morphology was observed in the dissimilar weld region. XRD analysis of the dissimilar welds confirmed the presence of only α and β phases, with no peaks corresponding to unwanted phases like titanium oxides. Non-uniform mixing of solute particles was observed throughout the weld region, where lightweight aluminium exhibited superior mobility and was almost uniformly distributed. In contrast, the heavier vanadium appeared less mobile, with greater variation in its weight percentage throughout the weld. Welds produced using pulsed-GTAW showed relatively better solute mixing and more uniform particle distribution compared to those produced using conventional GTAW (without current pulsing).

An unsymmetrical variation in hardness was observed across the weld region for the welds prepared using pulsed-GTAW. Non-standard reduced-section and standard tensile test specimens were prepared to assess the strength of the weld region and the weakest region of the weldment, respectively. Results from the reduced-section tensile specimens revealed higher strength for welds prepared using p-GTAW than for those prepared with conventional GTAW. The standard tensile specimens fractured in the HAZ of the CP-Ti, identifying it as the weakest region of the weldment.

Charpy impact tests were conducted on weldments prepared using both conventional-GTAW and pulsed-GTAW at a frequency of 5 Hz, with notches placed in different regions. A decrease in impact energy was observed in both the HAZ and weld regions of welds prepared using p-GTAW, compared to those prepared using conventional-GTAW. The zone-wise investigation of impression creep behaviour (in base CP-Ti, HAZ CP-Ti side, dissimilar weld, HAZ Ti-6Al-4V, and base Ti-6Al-4V) was also carried out for high-temperature applications. The presence of coarse prior-β grains and Widmanstätten morphology in the HAZ of Ti-6Al-4V and the weld zone contributed to reduced grain boundary sliding and impeded dislocation glide, respectively, resulting in improved creep resistance in these regions.

Thus, the study concludes that pulsed-GTAW can be successfully employed for the dissimilar welding of titanium alloys. Key conclusions arising from this experimental work on the dissimilar welding of CP-Ti and Ti-6Al-4V using pulsed gas tungsten arc welding are presented below.

1. 2 mm thick CP-Ti and Ti-6Al-4V sheets were autogenously welded using conventional GTAW and pulsed GTAW at a frequency range of 3-5 Hz in intervals of 0.5 Hz using optimized pulsed parameters. All the prepared welds

passed the X-ray radiographic test and were free from any kind of subsurface defects.

2. Welding parameters, including pulsed parameters, were selected and optimized by performing systematic experimentation to obtain welds with minimal heat input, avoiding grain coarsening and thermal damage due to welding heat. Some of the welding parameters used to achieve tailored welds were a 250 mm/min welding speed, 2.4 mm electrode diameter, 100-105 A welding current range, 10.5-11 V welding voltage, 1.5 mm stand-off distance, 60° electrode tip angle, 5 Hz pulsed frequency, 40% of peak current as background current, and 70% of the total cycle time as time for background current.
3. An indigenously designed shielding setup has been developed and assembled with a pulsed-GTAW machine. This shielding setup successfully protected the weldment from atmospheric contamination without requiring additional shielding, such as box shielding or trailing cups, and an atmospheric contamination-free silvery bright colour was obtained at the top and root of the weld. The shielding provided using the ceramic nozzle of the GTAW torch (primary shielding) during welding was temporarily retained, thus protecting the weldment from atmospheric contamination even after the completion of welding.
4. A mixed and complex microstructure appeared in the HAZ and weld regions. Due to the relatively high heat input and low thermal conductivity of titanium alloys, grain coarsening was observed in both the weld and HAZ. Within the prior-β grains in the dissimilar weld region, as well as in the HAZ of Ti-6Al-4V, fine α laths with β at the grain boundaries were observed. Current pulsing

during GTAW helped reduce the size of prior-β grains and refine the internal features within them, this effect was further enhanced by increasing the pulse frequency.

5. The weld region exhibited non-uniform mixing, with variation in solute weight percentages observed throughout the weld. Lightweight aluminium, having better mobility, showed more uniform mixing across the weld. This non-uniform mixing led to a differential microstructure throughout the weld. However, XRD results confirmed that no new phases appeared in the weld region beyond the existing ones.
6. The hardness observed at the center of fusion zones of conventionally-GTAW welded and pulsed-GTAW (5 Hz) welded samples was 281 $HV_{0.2}$ and 286 $HV_{0.2}$, respectively. The hardness gradually increased from the base metal of CP-Ti to the weld and then to the base material of Ti-6Al-4V. The base of Ti-6Al-4V exhibited the maximum hardness (345 $HV_{0.2}$) in the weldment. HAZ softening was observed in Ti-6Al-4V, which was absent in the HAZ of CP-Ti. No abrupt high hardness was seen in the form of peaks throughout the weldment.
7. During tensile testing, all the specimens fractured within the gauge length, and the strength of the welded specimens was found to be close to that of the as-received CP-Ti. The welded specimens prepared using conventional GTAW fractured near the base/HAZ interface of CP-Ti, but the fracture point changed near the HAZ/fusion boundary of CP-Ti. The current pulsing during welding helped improve the strength from 254 MPa to 300 MPa. Near-ductile fracture was observed in all specimens.

8. Charpy testing of welded specimens revealed that the current pulsing during welding increased the formation of hard phases in the weld, resulting in a slight decrease in impact energy. There was very little variation with frequency change; however, a slight drop in impact energy was observed with increasing frequency.
9. Impression creep test of different zones revealed that, 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.