Chapter 5 Conclusions and future work

5.1 Contributions from investigations

The present investigations are carried out on dissimilar Cu-Al FSW for its tool design, process parameters and hybrid FSW which are not presented previously to the best of author's knowledge. The mechanisms and properties of dissimilar Cu-Al FSW joints are elucidated in the present investigations. The individual effects of process parameters such as tool pin offset, welding speed and tilt angle are established on dissimilar Cu-Al FSW. The FSW process window is enlarged through hybrid approaches of assisted heating and cooling. The effects of assisted heating and cooling of FSW are studied for dissimilar Cu-Al joints.

In order to attain global aim of the work, there are five publications, published in high impact science citation index journals under the scope of present investigations. In addition to this, three research articles are presented in international conferences, out of this, two articles are published in international journals. One research article is presented in national seminar [refer Appendix – III for list of publications and reprint of articles].

Main contributions from the present investigations are as follows:

- Tool design

  Important components of tool design such as tool pin profile, pin diameter, shoulder diameter and shoulder to pin diameter ratio are investigated and its effects are established for dissimilar Cu-Al FSW system.

- Process parameters

  Process parameters of dissimilar FSW such as tool pin offset, tool tilt angle and welding speed are studied.

Influences of process parameters on properties of dissimilar Cu-Al FSW are established.

- Heating assisted FSW
  Gas tungsten arc welding assisted FSW is implemented as heating assisted technique for dissimilar Cu-Al system.

  Effect of preheating current on properties of dissimilar Cu-Al system is established.

- Cooling enhanced FSW
  Cooling enhanced FSW is developed under the effect of compressed air and water for dissimilar Cu-Al system.

  Hybrid approaches of heating and cooling assisted FSW are compared with normal FSW for dissimilar joint properties.

  Cooling enhanced FSW approach is identified as best suitable hybrid approach for dissimilar Cu-Al joints through which significant improvements of joint properties are achieved.

Mechanical and metallurgical properties of dissimilar Cu-Al welds are examined under the effect of above factors. Complex microstructures and presence of different IMCs phases are reported in the stir zone. Composite type microstructures are reported in the stir zone of dissimilar joints. Super hard and brittle type stir zone is reported in most of the cases. The maximum tensile strength of 158 MPa is reported with cooling enhanced FSW under the effect of water.

5.2 Conclusions

Conclusions of present investigations are presented as under through three different sub-categories such as (a) general conclusions, (b) effect of tool design and FSW process parameters and (c) hybrid dissimilar FSW.

(a) General conclusions

- Dissimilar Cu-Al joints are produced by friction stir welding technology.

- FSW process parameters such as tool design, tool pin offset, work-piece positioning, rotational speed, welding speed, tilt angle governs mixing of dissimilar materials and subsequently properties of Cu-Al joints.

- Dissimilar Cu-Al FS welded joint consisted composite type stir zone wherein Cu particles are reported in Al matrix. Complex and heterogeneous microstructures are reported in the stir zone due to different size and shape of Cu particles in Al matrix.

- Material flow of dissimilar Cu-Al stir zone is affected by shape and size of Cu particles dispersed from Cu base material.

- Phases of IMCs such as CuAl, $CuAl_2$, Cu_3Al and Cu_9Al_4 are presented in the stir zone of dissimilar Cu-Al joints.

- Formation of IMCs are reported in layer form at the interface between Cu-stir zone and around dispersed Cu particles.

- Interface of Cu-stir zone (i.e. thermo-mechanically affected zone of Cu side) is found as weakest zone of dissimilar Cu-Al FS welded joint as major IMCs are reported at this interface in layer form.

- Non-uniform hardness profile is reported across the cross section of dissimilar Cu-Al FS welds. Most of the stir zones are reported as "∩" shape profile hardness wherein maximum hardness is reported at the stir zone.

- Super hard stir zone is reported due to presence of different intermetallic compounds (IMCs).

- Dominant brittle fracture features are reported for most of the tensile specimens. Poor fracture to the elongation is observed for most of the welds.

(b) Effect of tool design and FSW process parameters

Investigations on tool design and process parameters of dissimilar copper to aluminum materials are carried out. Following specific concussions are drawn.

- Taper tool pin profile is unsuitable for Cu-Al dissimilar butt joint of FSW, wherein non-uniform mixing of both the materials is noticed. Major defects are reported at bottom of stir zone.

- The polygonal tool pin profiles are responsible for major defects in the stir zone due to uneven dispersion of Cu particles from Cu base material.

- Fragmental defects are increased as the number of polygonal edges decreased. Therefore, polygonal pins are unsuitable for dissimilar butt joint configuration.

- On the other hand, the cylindrical tool pin profile is observed most suitable, by which defect free dissimilar joint is obtained.

- The tensile strength of dissimilar Cu-Al joint is increased as the number of polygonal edges increased.

- Maximum tensile strength of 89 MPa is observed at joint made by cylindrical tool pin profile.

- Defect free dissimilar Cu-Al friction stir welds are achieved by tool tilt angles 2°, 3° and 4° whereas major defects are reported for tool tilt angles 0° and 1°.

- Macro-hardness in stir zone is increased as tool tilt angle increased.

- Effect of flash is reduced as tool tilt angle increased.

- Formation of IMCs is increased as tilt angle increased. In addition to this, $CuAl_2$ and Cu_4Al_3 IMCs are identified in stir zone area for tilt angle 0˚, whereas Cu_9Al_4 and Cu_3Al are identified in stir zone for tilt angle 2˚.

(c) Hybrid dissimilar FSW

Hybridization of FSW for dissimilar Al-Cu system added new process parameters through which joint properties can be governed remarkably. Concluding remarks are as under.

- Heating assisted FSW at low preheating current is attributed to improve the tensile strength up to some extent, while major defects are reported at higher preheating currents that consequently deteriorated the tensile strength.

- Besides, significant improvement in tensile strength is reported for cooling enhanced FSW technology relative to Normal FSW and Heating FSW.

- The maximum tensile strength of 158 MPa is reported at CFSWwater.

- Surface oxide formation is observed in case of HFSW while no surface oxide formation is noticed at NFSW and CFSW.

- NFSW and hybrid FSW are contained IMCs such as $CuAl_2$ and Cu_9Al_4, along with solid solutions of Cu and Al, identified through XRD analysis.

- The amount of IMCs formed in stir zone is increased with increase in preheating current in case of HFSW, while the formation of IMCs is drastically reduced with cooling effect in case of CFSW relative to NFSW. Minimum amount of IMCs is reported at CFSWwater based on the intensity peak from XRD analysis.

- Increase in hardness of stir zone is reported for hybrid FSW relative to NFSW. Formation of hard and brittle IMCs is attributed to rise in hardness for HFSW, while fine grain micro structure is responsible for higher hardness of stir zone in case of CFSW.

5.3 Suggestions for future work

- Complex tool designs such as bobbin tool, stationary tool, trivex and trifluete pin profiles can be studied for its effects on dissimilar Cu-Al FSW.

- Mathematical modelling can be developed in order to provide support to the experimental results.

- The investigation can be extended for combined effects of process parameters on dissimilar Cu-Al FSW as well as for the hybrid FSW.

- Single and Multi objective optimization methods can be applied to the results of present experimental studies.

- Different joint configurations of dissimilar Cu-Al FSW can be further investigated.

- Dissimilar Cu-Al system can be developed for different welding processes such as laser beam welding, gas tungsten arc welding and ultrasonic welding.