CHAPTER 9

CONCLUSIONS

9.1 DEVELOPMENT OF FRICTION STUD WELDING MACHINE

In the present work, a PLC based low cost Friction Stud Welding machine is developed for joining of studs up to a diameter of 12mm with similar or dissimilar metals. The newly developed welding machine is made by the transformation of a lathe with certain modifications. The in house made friction stud welding machine is eco-friendly and cost effective.

It offers the following benefits when compared to conventional arc stud welding:

- Similar and dissimilar studs can be welded with ease.
- No defects due to solidification, since there is no melting.
- No filler, flux, consumables or shielding gases required.
- Eco-friendly, no smoke, fumes, or gases
- No weld spatter
9.2 JOINING OF AA 6063 AND AISI 1030 STEEL

Experiments were conducted by varying the process parameters in the newly developed friction stud welding machine. The strength of the friction welded joints was evaluated. The effect of process parameters such as the speed of rotation, friction time, friction pressure on axial shortening distance and impact strength of the welded joints were studied. The following conclusions could be drawn from the study:

- Optical micrograph shows distinct DRX region of about 240µm on AA 6063 side very near to the joint interface.

- In the dynamically recrystallized region very fine recrystallized grains are observed through scanning electron microscopy inspection. This would enhance the strength of the joint.

- SEM micrograph reveals the presence of three distinctive regions in the heat affected zone namely, fully plasticized deformed zone, partially deformed zone and unaffected base metal zone. The dissipation of frictional heat from the weld centre results in temperature gradient across the welded joint, causing different zones with different microstructures.

- SEM-EDX analysis confirms the presence of oxides and the formation of inter metallic compound (FeAl) in the interfacial region. When the friction time is increased more heating takes place in the interface and metal oxides are forced to come out in the form of flash. However, higher friction time leads to more material consumption and tendency to form brittle intermetallic compound which is detrimental to the strength of the joint.
• Hardness value at the interfacial region is found to be higher than the hardness of the parent metals. 19.5% increase in hardness in the AA 6063 side and 18.7% increase in the AISI 1030 steel side are observed in the micro hardness profile. This is due to increased plastic deformation and grain refinement.

• The impact strength of the friction welded AISI 1030/AA 6063 steel joint is found to be 14.3% and 43.75% lower than that of AISI 1030 steel and AA 6063 respectively. The decrease in impact strength may be endorsed to the occurrence of oxides and formation of brittle inter metallic compound.

• The impact strength increases as the speed of rotation increases. This can be attributed to the fact that the increase in the speed of rotation minimizes the formation of inter metallic compound. It is found that the axial shortening distance increases with the increase of rotational speed. This is due to the increased heat generation rate at the interface when the rotating speed is increased.

• Impact test results show that the joint strength increases with increasing friction time. This is due to the increase in plastic deformation in the friction stud welded at longer friction time. Hence, an increase in friction time, leads to wider heat affected zone and narrower fully plastically deformed zone. Thus, greater volume of viscous material is transferred out at the interfacial region and this attributes to the increase in joint strength. However, with longer friction time above 10 seconds results in more amount of material consumption and decrease of joint strength.
In friction stud welding process much lower friction pressure is applied when compared to friction welding process. Experimental results show that friction pressure has least effect on the strength of the welded joint in friction stud welding process.

9.3 JOINING OF AA 6063 AND AISI 1030 USING INTERLAYER

In the present work, friction stud welding of AISI 1030 and AA 6063 was carried out successfully by varying thickness of AA 1100 interlayer. The following conclusions are drawn from the experimental investigation:

- Use of interlayer enhances the strength of the joint and makes it comparable to that of parent metals. The interlayer acts a buffer to reduce the heat affected zone and intermixed zone that appears near the weld interface has a tendency to reduce the thickness of brittle inter metallic compound at the interface. It is found that 40.97% increase in impact strength could be achieved when AA1100 interlayers are used in friction stud welding of AA 6063/AISI 1030 joints.

- Use of interlayer minimizes the consumption of metals since the axial shortening distance is reduced. On an average 21.33% reduction in material consumption could be achieved with the use of interlayer.

- SEM micrographs reveal the thickness of the intermixed zone as 9 microns, 16 microns and 42 microns for interlayer thickness 0.50mm, 0.95mm and 1.30mm respectively. With 0.95mm interlayer, higher impact strength of the AISI 1030/AA 6063 joint is achieved. This can be attributed to the uniform intermixing zone observed in SEM micrograph. Since
the thermal gradient is lower, the heat affected zone becomes narrower in case of 0.95mm interlayer.

- EDX analysis detects the presence of FeAl intermetallic compound at the weld line. With the use of interlayers, the peak temperature at the interface is lowered and it results in formation of thin inter metallic compound with lower hardness.

- SEM evaluation on the fractured surface of the specimens was carried out. Cleavage fracture showing river pattern observed with 0.5mm interlayer and brittle-ductile mixed mode fracture observed with 1.3mm interlayer. Ductile mode fracture with dimples observed with 0.95mm interlayer. Micro voids absorb a lot of energy, and the toughness is high. Hence, the dissimilar joint made using 0.95mm interlayer have high joint strength.

- The experimental data are analyzed using analysis of variance (ANOVA) to identify the significant contributing factors of joint strength. It is observed that the rotational speed and sheet thickness of interlayer are the most significant parameters that have high influence on impact strength.

- Rotational speed governs the coefficient of friction and plays an important role in minimizing the formation of intermetallic compound. From the contour plot, it is observed that impact strength is higher when the rotational speed is in the range of 1300 to 1600 rpm and interlayer thickness in the range of 0.75 to 1.05mm.
A regression model is developed to predict impact strength in terms of rotational speed, interlayer sheet thickness, friction time and friction pressure.

9.4 JOINING OF HYBRID AA 6063 MATRIX COMPOSITE AND AISI 1030 STEEL

The present work shows that SiC and graphite reinforced aluminium hybrid composite can be friction stud welded to AISI 1030 steel successfully using AA 1100 interlayer.

- Micro hardness profile shows increase in hardness value at the fully plasticized deformed zone of the interfacial region. This is due to the plastic deformation caused by upsetting pressure.

- Micro structural examinations reveal three separate zones namely fully plasticized zone, partially deformed zone and unaffected base material zone. Ultra-fine dynamically recrystallized grains of about 341nm are observed at the fully plasticized zone.

- EDX analysis confirms the presence of intermetallic compound at the joint interface. It is identified as \( \text{Fe}_2\text{Al}_3 \), which has cubic structure. Increase in the micro hardness could also be attributed to the presence of \( \text{Fe}_2\text{Al}_3 \).

- SEM micrograph at the fractured surface shows features with flat planes, sharp edges, and cracks. Trans granular cleavage fracture has occurred through the grains along crystallographic cleavage planes. River pattern of micro cracks is also visible in
the micrograph. Hence, brittle mode of fracture has occurred in the impact specimen.

- Rotational speed and interlayer sheet thickness contribute about 39% and 36% respectively in determining the impact strength of the welded joints.

- It is observed that rotational speed is the most significant factor with 71% contribution in determining axial shortening distance. When the rotational speed increases heat input increases due to the stirring action. The softened HMC material flows out as a flash covering the steel and more material is consumed resulting in increase of axial shortening distance.

- Based on the experimental results, regression model has been developed to predict impact strength and axial shortening distance with reasonable accuracy.

9.5 NUMERICAL SIMULATION USING ANSYS

Thermal effects during friction stud welding of mild steel-Aluminium were investigated through numerical simulations using finite element analysis. The following conclusions can be drawn from the study:

- Online temperature measurement at weld interface of mild steel Aluminium combination is done using a non-contact Infrared thermometer and time-temperature profile is generated. Measured data is used for validation of numerical model.

- Numerical simulation of friction stud welding process using ANSYS has been carried out and the simulated results are
compared with experimental results. The simulation results are in good agreement with the experimental values for friction stud welding of mild steel-aluminium combination.

- Using the non-linear numerical model, nodal temperature and heat flux during the continuous friction stud welding process are predicted.

- A simple mathematical model is developed based on finite element analysis of one dimensional heat flow. The analytical results are compared with that of the numerical results generated by ANSYS. A fair agreement is observed between the analytical and numerical results.

- Numerical investigation of heat flow in friction stud welding process has been carried out with small time increments. Results show that the heat dissipation is high on aluminium side whereas the heat dissipation is less in the mild steel side. This is due to the change in material properties of the two dissimilar metals. Since the thermal conductivity of aluminium is high the heat transfer is high on the aluminium side.

- The welded aluminium/mild steel joint shows marks of heat affected zone near the weld interface only on the mild steel side. This further confirms the predicted numerical results by numerical model. Because of the low thermal diffusivity of mild steel, the heat flow is confined to the region near the weld interface and results in visible appearance of heat affected zone on the mild steel side.
9.6 THERMAL MODELING OF FRICTION STUD WELDING PROCESS

- The model of Rykalin et al considers a continuous (plane) heat source in a long rod of semi-infinite length. Though this assumption holds good for friction welding, it is less appropriate for friction stud welding process. Hence a simple pin fin thermal is developed for friction stud welding process.

- Applying the first law of thermodynamics and Fourier’s law of heat conduction, a second order differential equation has been developed. Temperature distribution, heat flux and nodal temperature, during friction welding of aluminium and mild steel are predicted using the developed mathematical model.

- The temperature profile is broader in aluminium side where as it is narrower in the mild steel side. This trend could be attributed to the higher thermal conductivity of aluminium and lower thermal conductivity of mild steel. The temperature decreases along the length of the cylindrical rod.

- A finite difference modelling approach based pin fin model is developed to carry out transient analysis. The implicit method of formulation for the Finite Difference Method (FDM) is solved by means of thermal resistance – capacity formulation, because it could be easily adapted to thermal property variations with respect to change in the temperature.

- When compared with the measured data at a distance of 5mm and 10mm from the weld interface, the numerical values show
fair agreement with the experimental values. The computed temperature profile is not exactly matching with the experimental data, particularly in the cooling part. This is due to zero axial shortening assumption in the FD model.

- Since, friction stud welding process takes place in a very less time; this finite difference based model could be used as a tool to predict the thermal cycle and temperature distribution for small time increments. Thus the obtained graph helps to study and predict the temperature distribution of both the materials. Knowledge of thermal distribution could be used as a tool for predicting the heat affected zone and micro structural evaluation.

- This heat transfer model could be used as a tool to predict thermal cycle during the process and temperature distribution in the welded joints. Though one dimensional FD numerical model proposed in the present work cannot replace a more accurate numerical analysis, it does provide better understanding of the friction stud welding process.

9.7 SCOPE FOR FUTURE WORK

- Friction stud welding has many applications in marine engineering. A cost effective light weight portable friction stud welding machine could be developed. Pneumatic drive with air motor could be used to increase the process efficiency.

- Friction stud welding has many applications in under water welding. Experimentation could be done in underwater
conditions. Effect of process parameters on joint strength could be investigated.

- For more meaningful study about the thermal effects during friction stud welding, experimentation could be carried out using a series of thermocouples kept at regular intervals, along with infra-red detector.

- Experimentation could be carried out in an inert atmosphere to prevent the formation of oxides at the joint interface.

- The numerical model developed using ANSYS could be extended for coupled thermo-mechanical analysis of friction stud welding process.

- The micro annulus heat generation process could be extended to two dimensional finite difference model. This is because the heat generation varies from the centre of the joint to its periphery.

- Artificial Neural Network model could be developed to predict the time-temperature profile of friction stud welding process at different welding conditions.

- Process optimization could be carried out using soft computing techniques such as genetic algorithm and simulated annealing technique.