CHAPTER 6

SUMMARY OF RESULTS AND CONCLUSION

6.1 SIMULATION OF THERMAL CYCLES AND RESIDUAL STRESSES

A detailed non linear thermo-mechanical finite element model (NLTMFE) has been developed to simulate the thermal cycles and residual stress distribution in FSW of aluminum alloy 2014-T6. Nine welding cases with three tool rotations of 355, 710 and 1120 rpm and three welding speeds of 30, 60 and 120 mm/min were considered for simulation. For nine welding cases, the simulated peak temperature at weld zone is less than the melting point of the material aluminum alloy AA2014-T6. The difference of the maximum temperature at the same location (i.e., weld center) is less than 170 K for the entire set of parameters considered.

Using NLTMFE model, the stress fields in the welded plates were simulated to find out the nature of distribution. The effect of fixture release after welding was included in the model. The longitudinal stress perpendicular to the weld direction was predicted using the finite element model.

Temperature measurement and residual stress measurements were carried out to check the validity of the NLTMFE model developed for butt joint by FSW process.
On-line temperature measurement was conducted for the nine welding trials using thermocouples interfaced with LabVIEW software through a proper DAQ system to accurately measure the temperature data. The simulated and experimental data were compared and found that they matched fairly well.

Residual stress measurement was carried out for three samples. The simulated and experimental longitudinal stress component was compared to ensure the validity of the elasto-plastic model. The comparison shows that the simulated stress components are in agreement with the measured values.

To check the validity of the model, the simulated and experimental data were statistically analysed by student’s t-Test. The results show that the t-Stat value is less than the t-Crit. So the errors associated with the simulated data are insignificant. Thus the model developed is reliable to predict the thermal cycle and residual stresses of butt joints produced by FSW under different welding conditions.

6.2 INFLUENCE OF THE PROCESS PARAMETERS ON THERMAL HISTORY

It is observed from the thermal cycle that for given welding speed, higher tool rotation resulted in higher energy input per unit length of the weld. From the statistical analysis, it is observed that temperature at weld zone is more influenced by the tool rotation than welding speed.
6.3 INFLUENCE OF THE PROCESS PARAMETERS ON RESIDUAL STRESS

Using NLTMFE model, the stress fields in the welded plates were simulated to find the nature of distribution. The longitudinal stress perpendicular to the weld direction is predicted and validated with experimental values using statistical error analysis.

From the simulated and experimental residual stress data, it is observed that the magnitude of longitudinal residual stress in welded specimen is proportional to the tool rotation.

6.4 INFLUENCE OF THE PROCESS PARAMETERS ON MECHANICAL PROPERTIES AND MICROSTRUCTURE

ANOVA analysis of tensile property data of joints shows that the welding speed is the main input parameter that has the highest statistical influence on tensile properties.

Tensile strength increases with increase of revolutionary pitch upto 0.11 mm/rev. Under the condition of optimum revolutionary pitch 0.11 mm/rev, the tensile strength of the joint is maximum which is equivalent to 78 % that of the base metal.

Hardness data measured across the weld specimen were correlated with the peak temperature experienced by the same locations. The correlation shows that grain coarsening and dissolution of precipitates take place at temperature higher than around 500 K. The part of the weld zone which experiences the temperature more than 600 K, produces the same hardness as that of solution treated material.
From the microstructutal analysis, the welding parameters, tool rotation, welding speed affect the grain size in the nugget region of the weld. At a fixed welding speed, an increase in TR increases the grain size due to the higher heat input. At fixed tool rotation there is little change in grain size when changing the welding speed.

6.5 CONCLUSION

A 3D finite element model has been developed to study the thermal cycles and residual stress distribution in FSW of aluminum alloy AA2014-T6. Temperature and stress measurements were carried out to validate the NLTMFE model developed. To systematically study the influence of process parameters, nine experiments based on full factorial design were performed. The following points are summerised from the investigation.

1. The developed thermal model is useful to predict the temperatures at various zones of the friction stir weld

2. It is observed from the statistical test (t-Test, with 95% confidence level) of experimental and simulated temperature data that the value of t-Stat (0.680398) is less than the value of t-Crit one tail (1.651565). Hence, it is concluded from the statistical test that the simulated temperatures match with the experiment data.

3. From the thermal cycles, it is found that the peak temperature at weld zone is influenced by both tool rotation and welding speed. But from the statistical analysis (ANOVA) of the peak temperature, it is observed that the temperature at the weld zone is more influenced by the tool rotation (P = 82.67 %) than the welding speed (P = 15.05 %).
4. Using the mechanical (Elasto-plastic) model, the stress fields in the welded plates were simulated to study the nature of distribution. In the simulation, fixture release after welding was also considered to include its effect on stresses. The longitudinal stress perpendicular to the weld direction was predicted. Experimental and predicted stress values were compared. The errors associated with the comparison was analysed by t-Test. Since the value t-Stat (0.390201) is less than the t-Critical one tail (1.812462), the errors between the predicted and experimental stress values are insignificant.

5. From the FE analysis, it is found that increasing tool rotation increases the magnitude of longitudinal residual stress in the welded specimen.

6. From the ANOVA analysis of tensile strength data of joints, it is found that the welding speed is the main input parameter that has the highest statistical influence on tensile strength. Tensile strength increases with increase of revolutionary pitch upto 0.11 mm/rev then it decreases gradually. The tensile strength of the joint corresponding to the revolutionary pitch of 0.11 mm/rev is maximum which is equivalent to 78% that of the base metal.

7. Correlation of peak temperature across the weld direction with hardness shows that grain coarsening and dissolution of precipitates take place at temperature higher than around 500 K. That part of the weld zone which experiences temperature more than 600 K, gives the same hardness as that of solution treated material.
8. From the microstructural studies, it is observed that, at constant welding speed, an increase in tool rotation increases the grain size due to higher heat input, while at constant tool rotation there is little change in grain size due to welding speed variations.

### 6.6 SCOPE FOR FUTURE WORK

1. All the components of force developed during FSW can be measured and they can be included in the model to fine tune the results of the finite element model.

2. Material flow can be included in the model to quantify the residual stress pattern accurately.

3. TEM microstructure analysis of the weldments may be carried out to appreciate the effect of process parameters on precipitate dissolution.

4. To study the effect of process parameters on tensile properties, the width of the HAZ can be estimated and that can be correlated with fracture locations.