# CHAPTER 7

# CONCLUSION

In this research work, the warm deep drawing of AISI 304 austenitic stainless steel sheet material is investigated by experiments and FEM simulations. The forming characteristics, the maximum drawing load and strain measurements are successfully carried out and analyzed by a series of experiments, and simulations conducted on the stainless steel sheet material. Also, the analytical methods are used to calculate the thickness distribution, LDR values, height of the deep drawn cup and punch force.

The following important conclusions are drawn from the study and investigations on warm deep drawing of AISI 304 austenitic stainless steel sheet material in the investigated temperature range from the results of the experiments, FEM simulations, and analytical methods,

- The stainless steel components are deep drawn at all the investigated temperatures without defects.
- The maximum thinning occurs in the deep drawn cup at the punch corner radius region at all forming temperatures and the maximum reduction of thickness is 0.19 mm is obtained at 300$^{o}$C.
- The maximum increase in thickness is 0.27 mm observed at 100$^{o}$C and this helps the component to be stronger.

- The maximum drawing load is decreased by 37% in warm deep drawing process when compared with the conventional deep drawing.
- The strain in warm deep drawn components shows no significant change that may assist the possibility of fracture, when compared with that of the conventionally deep drawn components.
- No strain induced martensitic transformation in microstructure is observed in the warm deep drawn components.
- Variation of grain size is only 11μm in the warm deep drawing when compared to the conventional deep drawing. Hence, the grain size has no influence on the forming characteristics of AISI 304 stainless steel sheet.
- There is a noticeable variation in the micro-hardness with a maximum value of 115 HV in warm deep drawn components. This increase in hardness improves the strength of the components and it is not large enough to favour the fracture.
- Defects like cracking, tearing, necking are not observed in the microstructural investigation of warm deep drawn components of AISI 304 stainless steel sheet.
- Significant improvement in LDR value of approximately 23.8% is observed.
- The LDR value is improved from 1.93 to 2.39, when deep drawing is carried out at elevated temperatures.
- Also, it is possible to deep draw the component more than the height achieved in conventional deep drawing process. It is

seen that the height of the deep drawn cup is increased from 29.8 mm at room temperature to 48.6 mm at 300$^{o}$C with an increase of approximately 63 %.

- The FLD diagrams indicate that all the regions on the surface of the warm deep drawn components are not in the vicinity of fracture or necking even though there is a substantial increase in LDR and the height of the deep drawn cup.

- The results of the finite element simulations agree with the experiments in the occurrence of maximum thinning which is either in the punch nose radius region or just above the region in the deformed cup wall and also the regions on the top of the cup wall show the thickening effect both in experiments and simulations.

- Comparison between the FEM Simulations and experiments show that the required drawing load decreases as the temperature increases. The maximum variation of 15% is observed in required drawing load but only 8.70% variation between the two in reduction of drawing load when the temperature is increased.

- The maximum observed absolute variations in the true thickness strain between the simulations and experiments are only 9% in thinning regions and approximately 9% in thickening regions. Also, the maximum variation in thickness reduction between them is only 5%.

- The maximum absolute variation of 10.28% in true radial strain and 16.38% in true hoop strain is observed in finite element simulations.

- The results of FEM simulations with respect to the drawing load and thickness, radial and hoop strain compares reasonably well with the experimental values at all forming temperatures considered for investigation.

- From the analytical results, it is observed that the maximum variation in thickness variation when compared with those of experimental values is 0.17 mm with absolute variation of 15.32%. Thus, the new methodology used predicts the values very close to the experimental values.

- The maximum variations in determination of LDR, height of the drawn cup and the punch force by analytical method are 0.19, 4 mm and 8.26 kN respectively. The results of the analytical solutions show a reasonably good correlation with the experimental results in predicting LDR values, cup height and the punch force.

Thus, with the various advantages mentioned above over the conventional deep drawing, the warm deep drawing, is likely to become one of the sheet metal forming processes that will be widely used in the industries in future.

## 7.1 SCOPE FOR FURTHER WORK

Some of the possible research works that may be carried out in future are:

- Deep drawing of thinner sheets less than 0.5 mm which is considered to be an industrial challenge.
- Investigation on production of stainless steel sheets by different methods of manufacturing for improvement of formability.
- Use of draw beads of different shapes to study its effect on warm forming.
- Improved method of heating system in order to increase the productivity.
- Development of analytical methods to determine various parameters involved in warm deep drawing process.