CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The content of the entire thesis is summarized in this chapter. The originality of the research, summary of findings of the research, specific contribution towards industrial applications and recommendations for future research work are given briefly. In addition, the essential findings of chip morphology investigations are also described explicitly.

5.2 ORIGINALITY OF RESEARCH

The machining of super duplex stainless steel with liquid CO\textsubscript{2} as coolant (gas cooled machining) has been carried out. The machinability studies involves a detailed comparison among dry machining, wet machining and gas cooled machining. The material, super duplex stainless steel finds immense industrial applications. The material is considered as a difficult-to-machine material due to generation of very high cutting zone temperature during machining which thereby leads to a rapid tool wear. From the literature review, the analysis and optimization of machining parameters when turning super duplex stainless steel has not received much attention. In this research, Taguchi technique and response surface methodology are used for analysis and optimization of machining parameters.
The important contributions of research work to the existing knowledge base are given below:

1. The analysis of variance (ANOVA) clearly defines the significance of machining parameters and their interactions in influencing the corresponding output responses.

2. From the ANOVA table, the most dominant and the least dominant machining parameters can be found out based on their contribution percentage.

3. The optimization technique produced precise results on machining parameters and the corresponding output responses.

4. The composite desirability for predicting output responses is maximum (0.98036) in gas cooled machining.

5. The difference between the values of predicted output responses and the obtained experimental values (percentage of error) are minimum in case of gas cooled machining.

6. The performance of the output responses, surface roughness, tool flank wear, average cutting zone temperature and the cutting force gets considerably reduced in gas cooled machining when comparing with the dry and wet machining.

7. The values of predicted optimal machining parameters and the output responses in response surface methodology and Non dominated sorting genetic algorithm are much closer to each other.
8. Gas cooled machining changes the mode of chip formation and improves the chip tool interaction during the machining. It also increases the tool life from fatigue. The gas coolant can easily convect through the machining surface and reduces the operating temperature efficiently.

9. Gas cooled machining reduces the chip reduction coefficient and also the cutting strain. Thus it totally reduces the operation time, energy loss and increases the production rate.

10. For a high production rate, it is necessary to increase the feed rate and cutting velocity. But this in turn increases the running temperature and the tool wear, thereby reducing the tool life and surface roughness. To overcome all these defects, gas coolant is the best solution during machining.

11. Gas cooled machining has been found to be an excellent alternative to conventional dry machining and wet machining (using cutting oil). The problem of disposing conventional cutting fluid is avoided by using liquid CO₂. Cost wise, using liquid CO₂ is also economical (1Kg = 11 INR).

5.3. SUMMARY OF SIGNIFICANT FINDINGS

The following significant findings are drawn from the machinability studies on super duplex stainless steel with varying methods of cooling.

5.3.1 Dry Machining

In dry machining, the feed rate is the most significant machining parameter which influences the surface roughness, followed by the depth of
cut and the cutting speed. While in case of tool flank wear, the depth of cut is the most significant machining parameter followed by the cutting speed and the feed rate. Again the feed rate is the most significant machining parameter which influences the average cutting zone temperature followed by the cutting speed and depth of cut. Finally in case of cutting force acted along 'x' axis, the feed rate is the most dominant influencing factor followed by the depth of cut and the cutting speed. In short, out of the four output responses, the feed rate is the most dominating factor that influences three of the responses namely the surface roughness, average cutting zone temperature and the cutting force acted along 'x' axis. But the flank wear is highly influenced or dominated by the depth of cut.

Since the surface roughness is the "smaller the better" quality characteristics, the optimal values of machining parameters for obtaining minimum surface roughness are the second level of cutting speed (120 m/min), first level of feed rate (0.06 mm/rev) and second level of depth of cut (0.75 mm). Similarly the flank wear being "smaller the better" quality characteristics, the first level of cutting speed (100 m/min), third level of feed rate (0.10 mm/rev) and second level of depth of cut (0.75 mm) are the optimal values of machining parameters for obtaining the minimum values of flank wear.

Enormous amount of heat is generated while machining. It is necessary to maintain the cutting zone temperature to a minimum level. Since average cutting zone temperature is a quality characteristics of "smaller the better", the first level of cutting speed (100 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) are the optimal values of machining parameters for getting the minimum values of cutting zone temperature. Finally, the optimal values of machining parameters for obtaining minimum cutting force in dry machining is the second level of
cutting speed (120 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) respectively

Using response surface methodology, when considering all the output responses simultaneously, the optimal values of machining process parameters for dry machining are cutting speed = 120 m/min, feed rate = 0.06mm/rev and depth of cut = 0.6414 mm. The predicted values of output responses are, surface roughness = 1.4286 µm, flank wear = 0.0704 mm, average cutting zone temperature = 103.9546 °C and force acted along x axis = 150.0330 N respectively. The composite desirability for dry machining is 0.96996.

5.3.2 Wet Machining

In wet machining, the feed rate is the most significant dominating machining parameter that influences the surface roughness and average cutting zone temperature followed by the cutting speed and depth of cut. The tool flank wear mainly depends upon the depth of cut, followed by the cutting speed and the feed rate. Again, feed rate is the parameter which mainly influences the cutting force acted along ‘x’ axis, followed by the depth of cut and the cutting speed.

Since the surface roughness is the "smaller the better" quality characteristics, the optimal values of machining parameters for obtaining minimum value of surface roughness in wet machining is second level of cutting speed (120 m/min), first level of feed rate (0.06 mm/rev) and second level of depth of cut (0.75 mm. Since minimum flank wear is desirable, it is also a "smaller the better" quality characteristics and the first level of cutting speed (100 m/min), first level of feed rate (0.06 mm/rev) and second level of depth of cut (0.75 mm) are the optimal values of machining parameters for obtaining the minimum values of flank wear in wet machining.
The optimal values of machining parameters are the first level of cutting speed (100 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) for getting the minimum cutting zone temperature and the second level of cutting speed (120 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) are the optimal values for minimum cutting force.

Using response surface methodology, by taking into consideration all output responses simultaneously, the optimal values of machining process parameters for wet machining are cutting speed = 100 m/min, feed rate = 0.06 mm/rev and depth of cut = 0.5152 mm. Also, the predicted values of output responses are, surface roughness = 1.4036 µm, flank wear = 0.0807 mm, average cutting zone temperature = 62.7849 °C and force acted along x axis = 135.2167 N respectively. The composite desirability of wet machining is 0.94555.

5.3.3 Gas cooled Machining

In gas cooled machining, the feed rate is the most dominating machining parameter that influences the surface roughness and the cutting force acting along x axis followed by the depth of cut and cutting speed. In case of flank wear, the most influencing machining parameter is the depth of cut, followed by the cutting speed and the feed rate. Finally, when considering the average cutting zone temperature, the feed rate is the most influencing factor followed by the cutting speed and depth of cut.

The optimal values of machining parameters for obtaining minimum value of surface roughness in gas cooled machining are the first level of cutting speed (100 m/min), first level of feed rate (0.06 mm/rev) and second level of depth of cut (0.75 mm). During machining, since minimum flank wear is desirable, it is also a "smaller the better" quality characteristics.
The first level of cutting speed (100 m/min), third level of feed rate (0.10 mm/rev) and second level of depth of cut (0.75 mm) are the optimal values of machining parameters for obtaining the minimum values of tool flank wear in gas cooled machining.

The first level of cutting speed (100 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) are the optimal values of machining parameters for obtaining the minimum values of cutting zone temperature in gas cooled machining. Similarly for getting minimum cutting force along x axis the optimal values are the second level of cutting speed (120 m/min), first level of feed rate (0.06 mm/rev) and first level of depth of cut (0.50 mm) respectively.

By considering all output responses simultaneously and using response surface methodology, the optimal values of machining process parameters for gas cooled machining are cutting speed = 100 m/min, feed rate = 0.06 mm/rev and depth of cut = 0.5303 mm. Also, the predicted value of surface roughness = 1.0367 µm, flank wear = 0.0641 mm, average cutting zone temperature = 46.4795 °C and force acting along x axis = 130.0426 N respectively. The composite desirability for gas cooled machining is 0.98036.

5.4 RECOMMENDATIONS FOR FUTURE WORK

From the knowledge gathered and the findings observed during the research work, the following recommendations or suggestions are given for possible further improvements and investigations in experimental tests and analyses:

1. This research work can also be repeated by varying the gas applied for cooling like nitrogen, argon, compressed air, oxygen etc instead of CO₂ gas.
2. In this study, only three machining parameters namely the cutting speed, feed rate and the depth of cut are considered. Various tool geometry parameters like rake angle, nose radius, material of tool, type of tool can be varied in the future work.

3. Instead of machining super duplex stainless steel using CO$_2$ as coolant, the advanced methods like minimum quantity lubrication, refrigerant coolant etc can be employed and the results may be compared with the result of this work to decide on the best cooling methods.

4. The techniques employed for optimization can be varied like Genetic Algorithm, Neural Network, Fuzzy logic, Simulated Annealing, Ant colony Optimization etc instead of Response Surface Methodology.

5. The material under study can be varied like Inconel, Titanium, other grades of Steel etc and the same practice of applying liquid CO$_2$ as coolant can be followed.